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Engineering in the elementary science classroom: Teachers' knowledge and practice of the nature of engineering

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by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

This dissertation focuses on the *nature of engineering* (NOE) as an objective of engineering education efforts within the context of K-12 science education in the United States. The dissertation examines the NOE knowledge and teaching practices of participants in a research project aimed at supporting science and engineering instruction in grades 3-5. The project formed teaching triads of elementary student teachers, their cooperating teachers, and engineering graduate students. The engineers served as content area experts in science and engineering, areas which elementary teachers often have little preparation. Together with the teaching expertise of the student teachers and cooperating teachers, these triads incorporated engineering into their science instruction over the course of a semester.

The first part of this dissertation is an assessment of the NOE knowledge of study participants before and after their participation in the project. This work focused on a dimension of the NOE that has received considerable attention: the scope of engineering, or what does and does not fall under the umbrella of engineering work. Psychometric evaluation was used to refine a pre-existing survey so that it could adequately assess the scope of engineering. This refined survey was then administered to n=117 project participants as a pretest and a posttest. Using a mixed between/within-subject ANOVA model, this study found that participant knowledge of the scope of engineering increased significantly from pretest to posttest [$F_{(1,133)} = 48.116$, $p < 0.001$, partial $\eta^2 = 0.266$], and that this increase did not depend on the participant group (student teacher, cooperating teacher, engineering) in question [$F_{(2,133)} = 0.853$, $p = 0.429$, partial $\eta^2 = 0.013$]. Unexpectedly, the engineers did not show significantly higher scope of engineering knowledge than the teachers in the study [$F_{(2,133)} = 1.036$, $p = 0.358$, partial $\eta^2 = 0.015$]; while

expert in certain aspects of engineering, the engineers in the present study were not necessarily experts in the NOE.

The second study in this dissertation examined the engineering learning outcomes that were emphasized by project participants during the semester. All project participants completed semi-structured interviews at the end of their participation and were asked to describe what their students learned about engineering. Using qualitative content analysis on n = 138 interviews, participants' responses were categorized according to whether they discussed students' learning in terms of engineering *concepts*, *practices,* the *NOE,* or *affective* outcomes (e.g., attitudes toward engineering). The study found that project participants rarely discussed their students' learning of engineering concepts or of affective outcomes. Instead, participants discussed their students' learning of engineering practices and the NOE with great frequency. The frequent mention of NOE learning outcomes indicated that most participants valued the NOE as a learning goal in their classrooms.

The final part of the dissertation is an examination of how project participants communicated the NOE to students during instruction. A multiple case study approach was used to examine the engineering instruction of four triads over a semester, with a focus on how the NOE was conveyed during instruction. The study found that all four triads explicitly taught the NOE to students during the semester, although this occurred infrequently for all but one triad. All four triads also implicitly communicated many NOE messages to students via the engineering design activities they implemented in their classrooms. The implicit messages were generally less accurate than the explicit ones communicated by the triads, and often did not align with the NOE messages that the triads intended to communicate during instruction.

CHAPTER 1. OVERVIEW OF RESEARCH

Introduction

The publication of the National Research Council's *Framework for K-12 Science Education* (2012), followed by the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013) and their increasing adoption, represents a significant change for science education in the United States. Not only do these documents introduce a novel organizational structure for science concepts and practices, but they also place significant emphasis on engineering as part of science education. As stated by the NGSS, "Science and engineering are integrated into science education by raising engineering design to the same level as scientific inquiry in science classroom instruction at all levels…" (NGSS Lead States, 2013, Executive Summary, p. 1). The elevation of engineering design is evident in the NGSS's dimension of "Science and Engineering Practices." As more states adopt the NGSS, this means that engineering is becoming an increasingly significant component of science curricula at all grade levels. Although not all states have adopted the NGSS, most have adopted standards that include engineering in some capacity (Moore et al., 2015).

The focus of many K-12 engineering education efforts has primarily been on engaging students in design (Brophy, Klein, Portsmore, & Rogers, 2008; Dym, 1999; NAE & NRC, 2009). The NGSS retains a focus on engineering design, but also emphasizes engineering practices alongside scientific ones. Cunningham and Carlsen (2014b) argue that the NGSS treats engineering nearly exclusively as a set of design-related practices. They point out that even the NGSS's Disciplinary Core Ideas for engineering ("Defining and Delimiting Engineering Problems," "Developing Possible Solutions," and "Optimizing the Design Solution") are, in fact, design practices. Though the treatment of design practices within the NGSS has come under criticism (e.g., Cunningham & Kelly, 2017), the importance of engineering design practices for K-12 science and engineering education is undisputed within the engineering education literature.

Although engineering design is emphasized in the NGSS, a second important outcome for K-12 engineering education is for students to better understand the *nature of engineering* (NOE): what engineering is, what engineers do, and how engineering is related to other fields of study such as science (NAE & NRC, 2008; NRC, 2012). Although the "NOE" nomenclature has not entered common usage, many voices have called for learning outcomes related to the NOE (e.g., ITEA, 2007; Lachapelle & Cunningham, 2014; Moore et al., 2014). Many research studies, for instance, have investigated how teachers and students view the work of engineers (e.g., Capobianco, Diefes-Dux, Mena, & Weller, 2011; Chou & Chen, 2017; Cunningham, Lachapelle, & Lindgren-Streicher, 2006; Fralick, Kearn, Thompson, & Lyon, 2009; High et al., 2009; Montfort, Brown, & Whritenour, 2013). These studies all relate to the NOE even though they do not invoke the "NOE" construct, and while the terminology varies, studies and policy documents all agree that if engineering is to be part of K-12 education, then students ought to learn what about what engineering is and what engineers do.

Purpose

While interest exists in promoting K-12 students' understanding of the NOE, the research in this domain is scant, particularly at the elementary level. Most studies are exploratory, and a common set of constructs or terminology have yet to be established. Given the unexplored status of the NOE in K-12 education, a useful guidepost is the much further-developed field of *nature of science* (NOS) research. This field of research points to the teacher as the crucial factor in promoting students' development of an accurate understanding of the NOS. In order to accurately convey the NOS to students, teachers must sufficiently understand the NOS. This, however, is insufficient; teachers must prioritize teaching the NOS to the point where they explicitly address it with students (Lederman, 1999, 2007; Lederman & Lederman, 2014).

To what extent do the findings from NOS research apply to the NOE? Addressing this question requires that teachers' NOE knowledge and practice be examined. The present work focuses on laying a descriptive foundation for the NOE knowledge and practices of elementary teachers. If the goal is to support elementary teachers in accurately conveying the NOE, then descriptive work of this kind is an essential first step. Some studies have explored aspects of elementary teachers' NOE knowledge (e.g., Cunningham, Lachapelle, & Lindgren-Streicher, 2006; Lambert et al., 2007), but much more work is needed in this area. More importantly, no studies have addressed the extent to which elementary teachers prioritize NOE ideas during engineering instruction, or how they convey the NOE to students. Given the interest in promoting students' understanding of the NOE, the gap in knowledge of teachers' NOE practices needs to be addressed.

Defining the NOE Construct

Because the NOE is the central theme of this work, this section provides a detailed description of the construct. First, descriptions of the NOE in existing education literature are summarized, and parallels are drawn between the NOE and the related construct of the nature of science (NOS). Because the NOE is not well defined in the existing literature, a literature review was conducted to better define the construct. The review method is described, and the final section provides a detailed elaboration of the construct developed from the review.

Descriptions of the NOE in Education Literature

While systematic attempts to elaborate the NOE construct for education are few, several studies have attempted to define certain aspects of the NOE (e.g., Chou & Chen, 2017), or have put forth sets of ideas that students should understand about the NOE (e.g., Karatas, Micklos, & Bodner, 2011). Some studies have entered this space for ad hoc purposes of data analysis. For instance, in Chou and Chen's (2017) study of elementary students' drawings of engineers, they defined the "nature of engineers" (p. 477) in order to assess the accuracy of the drawings. Citing previously offered definitions of engineers (e.g., NAE & NRC, 2008), Chou and Chen stated:

> …the nature of engineers is to design and develop new solutions that meet people's needs on a daily basis by using scientific principles and technological tools. In other words, the role of engineers tends to extend to research and development of new products, with a focus on the maintenance of engineering equipment. (p. 477)

Similarly, Kőycű and de Vries (2015) conducted an international study of secondary students' conceptions of the engineering profession. To evaluate students' responses, they described engineering in terms of "research," "development," "managerial," and "economic and social" dimensions (p. 248). While they did not elaborate on these dimensions, they indicated that an accurate understanding of the field of engineering would include knowledge of each.

Another perspective is provided by Moore et al. (2014), who included a dimension for "Conceptions of Engineers and Engineering" in their *Framework for Quality K-12 Engineering Education*. They described this dimension as follows:

> K-12 students… should also come to an understanding of the discipline of engineering and the job of engineers. This includes some of the big ideas/conceptions of engineering, such as how their work is driven by the needs of a client, the idea of design under constraints, and that no design is perfect. (p. 5)

This description of what students ought to know about the NOE goes beyond separating engineering design from the work of car mechanics and construction workers, including ideas like the role of clients and constraints in engineering design. While providing some level of detail, this description of the NOE leaves many questions unaddressed, including: what role does a client play during engineering design, what sort of constraints must engineers consider, and how do constraints influence the design product? Elaborating on such questions was beyond the scope of the work by Moore et al.; their framework drew from engineering curricula and state standards, and the NOE ideas they discussed represented only one component of their framework.

A recent study by Cunningham and Kelly (2017) provided a detailed view of several NOE ideas. Their work addressed the NOE indirectly, as their primary objective was to elaborate a set of "epistemic practices of engineering" (p. 492) with which K-12 students ought to engage during engineering instruction. While this goal is separate from the goal of promoting student NOE understanding (Bell, Mulvey, & Maeng, 2012; Lederman & Lederman, 2014; Sadler, Burgin, McKinney, & Ponjuan, 2010), Cunningham and Kelly drew from the NOE to establish their list of practices. To construct their list, they built "a more robust understanding of engineering and how it works, [turning] to studies of professional engineering in practice and empirical studies of engineering in educational settings" (p.490). In their resulting list, Cunningham and Kelly (2017) provided more in-depth descriptions of the NOE than is found in other studies. An example can be found in their discussion of the engineering practice of teamwork:

> Effective communication occurs in social contexts as engineers work together in teams. These teams often include other engineers, but also clients, technicians, artists, or even politicians. Studies of engineering in practice note the importance of collaboration and the need to bring together expertise across types of knowledge (Anderson et al., 2010; Bucciarelli, 1994; Jonassen et al., 2005; Vincenti, 1990). (p. 494)

Not only does their discussion provide details of how teamwork plays out in the context of engineering work, the cited works are also studies of engineers, rather than engineering curricula or standards. Yet while Cunningham and Kelly provided useful descriptions such as these, their focus was on providing evidence for their list of practices, not on comprehensively elaborating the NOE. As a result, many NOE avenues were left unexplored; for instance, Cunningham and Kelly described several practices that engineers use to engage with engineering problems, yet they did not discuss the more fundamental question of what makes a problem an *engineering* problem. They also stated that engineers engage in the practice of utilizing scientific knowledge, and that engineering is not merely applied science, but they did not describe the complex interactions between science and engineering. These observations are not intended as criticism, but to draw attention to how their focus on practices affected their NOE discussions, and to highlight the work that remains to be done to more thoroughly elaborate the NOE.

A more direct attempt to formulate a description of the NOE based on studies of engineering was taken by Karatas, Micklos, and Bodner (2011), and they are among the few scholars to employ the "nature of engineering" term. They listed the following NOE characteristics:

> Engineering solutions are tentative (Koen 2003); involve designing artifacts and systems (Bucciarelli 2003; Dym et al. 2005; Lewin 1983; Vincenti 1990; Wulf 2002); depend on existing scientific mathematical theories as well as failures and successes in the field (Adams 2004); are affected by cultural norms and the needs of society (Adams 2004; Dym 1999; Dym et al. 2005); involve stepwise iterative and collaborative problem-solving activities (Bucciarell 2003; Dym 1994; Koen 2003; Vincenti 1990); require creativity, imagination, and the ability to integrate different scientific, mathematical and social values and theories in novel ways (Adams 2004; Rogers 1983); are the result of a complex human endeavor that requires analytical thinking to make complex problems simpler (Dym et al. 2005; Koen 2003; Matthews 1998); and are an holistic, open-system approach that requires considering all aspects and perspectives of not only artifacts and customers, but also its effects on the environment, individuals and society, and culture (Adams 2004; Mitcham 1998; Rophl 2002). (p. 125)

This list of statements was also utilized in a later NOE study by Karatas, Bodner, and Unal (2016). Several aspects of this list are noteworthy. First, many of the sources cited here are the same as those used by Cunningham and Kelly (2017), but Karatas, Micklos, and Bodner did not indicate how or why they selected the thirteen texts they cited. Second, and more importantly, several of the declarative statements on this list do not provide enough detail to give an informed view of the NOE. In what sense, for instance, are "engineering solutions" "tentative?" At some point, if an engineering design is used to create a physical artifact (e.g., a bridge); is that design still tentative? Engineering solutions might be impacted by “cultural norms and the needs of society,” but how and to what extent? “Social values” are mentioned, but this raises many questions about the complex values that underlie engineering, including profit or political motives. Further, is the consideration of “all aspects and perspectives” regarding artifacts and customers accurate, or even possible?

The various descriptions of the NOE offered by the above studies give a sense of the breadth of ideas that comprise the NOE. Understanding the NOE includes the social dimensions of engineering practice, the character of engineering design, the research activities of engineers, and much more. Yet while many different NOE elements have been identified, little direct discussion has occurred about what the NOE construct ought to include, and what K-12 students ought to know about the NOE. This is in sharp contrast to NOS research, where many ongoing and lively debates occur over how to describe the NOS construct for the purposes of K-12 education (cf. Irzik & Nola, 2011; Lederman & Lederman, 2014; Matthews, 2012). Given the parallels between the NOS and NOE, advances within the NOS research community can do much to inform the development of a robust NOE framework.

Guidance from the Nature of Science

Compared to NOS research, inquiries into K-12 teaching and learning of the NOE are in their infancy. In putting forth a description of the NOE construct, lessons learned from similar efforts in the NOS field can be informative. An area of considerable controversy within NOS research is the value of NOS tenets: lists of declarative statements that put forth reasonably supported views about science (cf. Lederman & Lederman, 2014; Abd-El-Khalick, 2014). Those who advocate for such lists often argue that they provide educators with useful touchstones on what can otherwise be dauntingly complex topics. On the other hand, tenet lists have been criticized on the basis that they obscure essential complexities and nuances within the NOS issue by making sweeping generalizations (cf. Clough, 2007; Efflin, Glennan, & Reisch, 1999; Hodson & Wong, 2014; Matthews, 2012).

Alternatives to "tenet lists" have been put forth, and a promising approach proposed by Matthews (2012) is to outline a collection of "features of science (FOS) to be elaborated, discussed and inquired about, rather than nature of science (NOS) items to somehow be learnt and assessed" (p. 15). For example, instead of stating that "scientific knowledge is tentative (subject to change)" (Lederman & Lederman, 2014, p. 601), Matthews suggests that a feature of science to investigate is its "tentativeness" (Matthews, 2012, p. 15). That is, rather than indicate that scientific knowledge *is* tentative, one can inquire as to the *extent* that it is tentative, and what it *means* for it to be tentative. A list of key features of science ought to include issues identified as important by scholars of science (including philosophers, historians, sociologists, and others), and which are also accessible and relevant for educational settings (Matthews, 2012). A similar approach is advocated by Eflin, Glennan, and Reisch (1999) who, in noting the complexities and nuances within the philosophy of science, recommend a "taxonomy of philosophic issues" (p. 112) as a starting point for NOS education.

Engineering, like science, is a complex endeavor, and putting forth well-supported yet informative declarative statements about the NOE is an extremely difficult, and perhaps impossible, task. Therefore, the NOE framework developed here follows the overall approach of Matthews (2012) and is presented as a set of "disciplinary features of engineering" that highlight areas of importance within the NOE for K-12 engineering education. Taking this type of approach provides an opportunity to elaborate upon each of the disciplinary features while also acknowledging their complexity. In addition, the approach acknowledges that while consensus might exist around which disciplinary features are important, many issues are still debated for each of those features.

Method of Developing Features of Engineering

Following the suggestions made by Matthews (2012), developing a set of disciplinary features of engineering requires examining the scholarship of those who have taken the discipline of engineering as an object of study. This approach was used by Cunningham and Kelly (2017) to generate a set of epistemic practices of engineering. A significant challenge, however, lies in the breadth of scholarship on engineering; a comprehensive review of the literature in this domain is impractical. The more modest objective pursued in the present work was to review *representative* works from the variety of disciplines that study engineering, including philosophical, historical, and sociological perspectives, as well as those from within the engineering field. Important disciplinary features of engineering could then be determined by identifying themes that cut across these varied perspectives.

To determine the set of disciplinary features of engineering that could be used throughout this dissertation, the review of representative works began with those cited by previous researchers to describe the NOE. These included works cited by Karatas, Micklos, and Bodner (2011) as well as Cunningham and Kelly (2017). This step was not intended to replicate prior work, but to ensure that important works were not omitted; Cunningham and Kelly, for instance, explained that they began their review with "seminal works in the field" (p. 491), and such seminal works were important to include in the present review (e.g., Bucciarelli, 1994; Vincenti, 1990). Note, however, that the focus of the present review on the NOE construct rather than engineering practices meant that these “seminal works” were interpreted with a different lens than used in the work by Cunningham and Kelly.

The review was then supplemented by relevant works selected from a recent extensive literature review conducted on the nature of technology (Pleasants, Clough, & Olson, under review). One of the major themes within the nature of technology literature, identified during that review, is the process by which technology are developed. Because engineering plays a significant role in technological development, the elaboration of this theme drew from many works that discussed the engineering discipline (e.g., Kroes, 2009, 2012; Mitcham, 1994; Norman, 2013; Petroski, 1994; Pinch & Bijker, 1987). All works related to that nature of technology theme were used to develop the disciplinary features of engineering presented here. A particularly important text that was identified during the nature of technology review is *Philosophy of Technology and Engineering Sciences*, edited by Meijers (2009); a considerable portion of this 1500-page handbook addresses historical and philosophical studies of the engineering discipline.

After reviewing the works described above, additional texts for the review were identified by following the citation trails within the reviewed texts. This “snowball” method has shortcomings in that it does not necessarily broaden the scope of a review effort. However, the broad net that was cast during the initial gathering of texts for the review meant that all of the targeted disciplinary perspectives (philosophy, history, sociology, engineering) were well represented in the review. Table 1.1 indicates several representative texts from each perspective, and texts used for the review are noted with an asterisk (*) in the references list of this chapter.

Table 1.1: Representative Studies of Engineering from Various Perspectives

Perspective	**Representative Texts**
Philosophy	Kroes (2012); Meijers (2009)
History	Petroski (1996); Vincenti (1990)
Sociology	Bucciarelli (1994); Bijker, Hughes, Pinch, & Douglas (1987)
Engineering	Cross (2000); Dym & Brown (2012)

Each text included in the review was examined for its discussions and perspectives on the nature of the engineering discipline. Many of the reviewed texts also discussed topics more distantly related to engineering, such as interactions between technology and society. Unless engineering figured prominently in such discussions, they were considered not to be relevant for the review. After reviewing several texts, a tentative set of themes were developed that described dimensions of the NOE addressed by multiple authors; such commonly-discussed themes were taken to indicate main points of interest in the field of NOE scholarship. Then, following a constant-comparative approach (Glaser, 1965), the list of themes was then iteratively refined as more texts were reviewed. The review process was concluded when the list of themes reached a point of stability. Each of the themes identified during the review was then included as a disciplinary feature of engineering. Together, these disciplinary features comprise the framework for the NOE construct used throughout this dissertation.

Elaboration of the NOE Framework

The results of the review of NOE scholarship yielded nine disciplinary features of engineering:

1. Design in Engineering
2. Specifications, Constraints, and Goals
3. Sources of Engineering Knowledge
4. Knowledge Production in Engineering
5. The Scope of Engineering
6. Models of Design Processes
7. Cultural Embeddedness of Engineering
8. The Internal Culture of Engineering
9. Engineering and Science

What follows are elaborations of each of these features, drawing attention to important issues and perspectives found in the literature. Because these features are meant to inform K-12 education, each is discussed at a level of generality that raises key issues while avoiding the highly technical nature of certain perspectives. For a more detailed view, the reader is encouraged to consult the texts used during the review, particularly those listed in Table 1.1.

As Matthews (2012) indicated, features ought to be “elaborated, discussed, and inquired about” (p. 15) during instruction. To this end, many questions are posed during the elaborations of the features, and while answers to these questions are sometimes offered, they should not be regarded as definitive. The intent is that the questions and perspectives will serve as a guide for the research studies described in chapters 2-4, as well as be useful when engaging teachers and students in conversations about the NOE. In addition, the questions and elaborations that follow provide guidance for other researchers interested in assessing individuals’ knowledge of the features.

1. Design in Engineering. Design has been argued to be a defining feature of engineering, one that separates it from disciplines such as science (Dym & Brown, 2012; Simon, 1996). Design, however, is not unique to engineering (Hughes, 2004; Simon, 1996), so how does engineering employ design in a way that is specific to the discipline? Kroes (2012) argues that engineering is unique in that it is primarily concerned with the *practical* design of *technologies*. While engineers might consider aesthetics as part of their designs (Kroes, Franssen, & Bucciarelli, 2009; Petroski, 1996), the artifacts they produce are primarily practical or functional in nature (Bucciarelli, 1994; Cross, 2000). In contrast, non-engineering designers might be primarily concerned with aesthetic appeal, or marketing and sales.

How does the practical/functional focus of engineering affect the process of engineering design? Engineers must attend to both the internal workings of a technology (its technical form) and to how the technology will be used by people (its function in a social environment). The challenge for the design engineer is how to move from an idea of how a technology must function to the internal structure that will produce that desired function (Dym & Brown, 2012; Kroes, 2012; Simon, 1996). While the physical form of an artifact does not completely *determine* its function (Feenberg, 2010), it must at least *permit* the desired function. How a designer manages to move from desired function to internal form remains somewhat mysterious; it cannot be achieved mechanistically or algorithmically, and requires great creativity (Cross, 2000).

The task of engineering design is often described as one of *problem-solving* (Dym & Brown, 2012), and the work of Herbert Simon (1996) has been particularly influential in this area. Simon argues that, although design situations are often ill-defined, these situations can be resolved into well-defined subproblems, each of which can be solved through rational procedures. Not all who study design view it as rational problem-solving. For example, Dorst and van Overveld (2009) argue that labeling design as a problem-solving activity obscures the fundamentally creative character of design. They argue that the essential task for the designer is in formulating (and often iteratively reformulating) the design problem itself, which is a highly creative process. While design includes some problem-solving activities, it includes other activities as well (Hatchuel, 2002).

What is produced by engineering design? Engineers do not physically produce technologies, but rather generate the specifications for a technology's fabrication (Dym & Brown, 2012). These specifications might be for a single artifact, a method of producing an artifact, or for a system of artifacts (Petroski, 1996). Because these designs are handed off to others for production, engineers must sufficiently describe the artifact for the purposes of production. Designs, therefore, typically include detailed drawings as well as textual and numerical information (Dym & Brown, 2012).

Another critical aspect of engineering design is that it typically requires the coordinated efforts of teams of engineers, each with various specializations, as well as technicians and scientists (Trevelyan & Tilli, 2007). Because technological projects involve many divisions of labor, and delegations of work to contractors and specialists, few engineers engage with more than a small component of any technological design process (Bucciarelli, 1994; Cross, 2000; Matthews, 1998; Vincenti, 1990). To what extent is the design of complex technologies fundamentally different than the design of relatively simple ones? Does engineering design take on a different character when it involves the coordinated efforts of large numbers of individuals? How much of engineering design is actually the *management* of diverse teams?

2. Specifications, Constraints, Goals. The above description of design takes for granted that the designers have a description of how a yet-to-be-designed artifact must function, but how is that description generated? How do engineers determine what qualities an artifact should possess? The design tasks that are posed to engineers often originate from an external source, such as the management of a technology firm or a client with whom a firm has a contract. When these tasks are presented to engineers, they are often ill-defined: while they might specify a goal to be achieved or a technological problem to be resolved, these are described only generally. Engineers must translate these ill-defined goals into specifications that can be used to guide design work (Bucciarelli, 1994; de Vries, 2009; Dym & Brown, 2012; Kroes, 2012; Matthews, 1994; Vincenti, 1990).

How do engineers go about this translation process? The task always takes place in a social context and can thus be highly complex. A team of engineers working on a project must negotiate how a successful design will be defined, in terms unambiguous to those involved (Bucciarelli, 1994). Vincenti (1990) presents an example of this process in his description of how airplane designers developed a set of *flying quality* characteristics. In the early 20th century, a goal for airplane design was to make them relatively easy and pleasant to fly, but this goal needed to be defined in much more concrete terms in order to be useful for designers. Research engineers therefore worked with test pilots to develop a set of quantitative specifications that defined the meaning of flying quality. Developing these specifications required extensive interactions and negotiations between engineers and pilots.

In addition to specifications for a successful design, engineers must also navigate various constraints on their designs. Design constraints are limitations placed on the designed technology in terms of safety, reliability, cost, or other factors (Cross, 2000; Kroes, 2012; Matthews, 1994). How do engineers determine which constraints need to be considered during design? These, too, must be socially negotiated, and are often renegotiated during the process of design (Bucciarelli, 1994; Dym & Brown, 2012). Engineers, for instance, must decide how much cost is too much, what kinds of safety tolerances must exist, and how reliable a device must be. While these are sometimes given to engineers as quantitative specifications or regulations, more often the designers must translate vaguely-stated constraints much as they translate specifications (Bucciarelli, 1994). Dym and Brown (2012), in fact, argue that constraints and specifications are essentially synonymous, and are treated by designers in the same fashion.

3. Sources of Engineering Knowledge. What knowledge do engineers utilize during design? While engineers clearly utilize knowledge from science and mathematics, consensus exists that engineering is not merely applied science, and that it has a knowledge base of its own (Houkes, 2009; Kroes, 2012; Vincenti, 1990). If this is the case, what is the nature of that knowledge base?

When engineers engage in the design of an artifact, they necessarily draw on their knowledge of existing artifacts (Cross, 2000). At times, engineers work within a well-explored technological area, in which the “normal configuration” (Vincenti, 1990, p. 209) of a device has been established. That is, the engineer knows to a significant extent how the various components that comprise an artifact ought to be arranged. Dym and Brown (2012) describe this situation as “routine” engineering design. Even when design is less routine, engineers can rely on analogies to connect known and unknown technological spaces (Cross, 2000; Petroski, 1996; Ozkan & Dogan, 2013; Vincenti, 1990). Even when working in novel domains, a designer must have a sense of what Polanyi (1958) calls the “operational principle” underlying a technology: an overall sense of how a device or system functions.

While connections exist between the areas of knowledge described above and scientific knowledge, they nevertheless represent a knowledge base that is independent from that of science. Even when engineers utilize theoretical knowledge, that knowledge often belongs to the domain of engineering rather than science. For instance, there are theoretical concepts in engineering that are tightly coupled to specific technologies; Vincenti (1990) describes several such theories that pertain specifically to components of aircraft, such as propellers or airfoils. Unlike scientific theories, which are used to understand natural phenomena, engineering theories are used by engineers for the practical purposes of design. If a theory cannot generate information for design, usually in the form of calculable quantities, then it is not of great interest to the engineer (Houkes, 2009).

4. Knowledge Production in Engineering. If a knowledge base unique to engineering exists, how is that knowledge developed? An important mode of engineering knowledge production, though not the only one, is engineering research, sometimes called “engineering science.” This form of engineering work is most visible in universities (Adams, 2004), but also occurs in industrial research and development laboratories (Channell, 2009; Vincenti, 1990).

How is engineering science related to, but separate from, the natural sciences? Both disciplines are concerned with the production of knowledge (Houkes, 2009). The methods employed by the two fields are also extremely similar, and they even have similar means of disseminating that knowledge, such as professional journals and conferences (Brase & Grunwald, 2009; Vincenti, 1990). However, the ultimate goals of the knowledge-producing activities of science and engineering science differ: for science, knowledge about natural phenomena is an end in itself, while for engineering science, the produced knowledge is only a means to be used for the purposes of designing technologies (Brase & Grunwald, 2009; Dym & Brown, 2012). While science aims toward understanding and explaining natural phenomena, engineers do not necessarily require explanation of the phenomena at hand. Rather, engineering science is content to generate models of phenomena that produce useful results, even if they offer little explanatory power (Houkes, 2009; Vincenti, 1990).

Because the goal of engineering science is on generating knowledge for use in design, engineering science generates knowledge *related to specific technologies* (Channell, 2009; Petroski, 1996; Vincenti, 1990). The products of engineering science might include knowledge of how particular technologies function, or analytical tools and models that can be applied to a range of technological phenomena (Dym & Brown, 2012).

5. The Scope of Engineering. Engineers work with technology, but technological activity in general includes much that is not engineering. With what parts of technological practice are engineers involved? While craftspeople typically are both the designers and producers of technologies, modern engineers are engaged not highly engaged in production. While engineers might design the methods for producing an artifact, they are not the ones to physically carry out the production (Cross, 2000; Dym & Brown, 2012; Kroes, 2012; Mitcham, 1994; Petroski, 1996). Similarly, although engineers must consider a technology's users when designing it, engineers are not typically intended to be the primary consumers or operators of a given technology (Norman, 2012; Trevelyan & Tilli, 20007; Vincenti, 1990).

Engineering work is, however, quite broad, and includes more than just technological design (Mitcham & Schatzberg, 2009). Many engineers engage in "engineering science" rather than design, which is a research-focused activity (Houkes, 2009; Petroski, 1996; Vincenti, 1990). Other engineers act as overseers of projects, particularly in the case of civil engineering (Florman, 1987). Instead of designing artifacts, engineers might also engage in studies of existing artifacts, particularly in the case of unexpected failure (Matthews, 1998), or be involved in certain maintenance activities (Mitcham, 1994; Trevelyan & Tilli, 2007). Given this range of activity, where is the boundary of engineering practice? Can certain practices be regarded as the "core" of engineering, with others as more "peripheral?"

6. Models of Design Processes. To what extent is there, or should there be, an overall structure to the process of design? This is the central question in the field of design methodology, the goal of which is to better understand and ultimately improve the engineering design process (EDP) (Banse & Grunwald, 2009; Kroes, 2002). Many models of the EDP, often in the form of flowcharts, have been put forth and reproduced in the literature (cf. Cross, 2000; Dym & Brown, 2012). These EDP models vary in terms of their level of generality; some include as few as three broad phases, while others specify many phases, each with multiple sub-phases (Dym & Brown, 2012; Pahl, Wallace, & Blessing, 2007). EDP models can either be *descriptive* by attempting to describe actual design practices, or be *prescriptive* by providing normative suggestions for what design ought to be like (Cross, 2000; Kroes, 2002).

Many questions surround these proposed EDP models. What is a desirable degree of specificity for an EDP model? Those that are too vague are not much use to those wanting to learn how to design (Dym & Brown, 2012), but adding too much detail can "obscure the general structure of the design process by swamping it in the fine detail" (Cross, 2000, p. 36). How do descriptive and prescriptive models of the EDP differ? Cross (2000) notes that many prescriptive EDP models place great emphasis on initial analysis and problem definition, yet examinations of expert designs typically reveal that they start generating potential solutions very early in the process (Dorst & Cross, 2001). While some models attempt to take this into account (e.g., March, 1984), many do not. Finally, there is the question of whether a generic EDP model is appropriate, given the breadth of engineering design work. Dym and Brown (2012) caution against regarding any model as "The" design process, and others question whether any EDP model can adequately capture the complex and context-dependent process of design (cf. Bucciarelli, 1994; Dorst & van Overfeld, 2009; Kroes, 2012; Mitcham, 1994).

Why do engineers seem to be so interested in generating EDP models, especially those in the form of flowcharts? This is not, for instance, something that is often seen within studies of science methodology (Kroes, 2002). One potential explanation is that a great deal of pressure is placed on design engineers to work quickly, with minimal costs, and with few errors; such efficiency pressures are far less apparent in science (Bucciarelli, 1994; Cross, 2000; Vincenti, 1990). These pressures call attention to the design process itself, and how to potentially improve it, which leads naturally to formal prescriptive models. EDP flowcharts can be useful when coordinating the efforts of large teams of engineers, which often occurs during the design of complex technological artifacts (e.g., airplanes) and systems (Cross, 2000; Kroes, 2012). They are also useful pedagogical tools for novice designers (Dorst & van Overveld, 2009). Dorst and Cross (2001) argue that EDP models are best regarded as tools for beginning designers, rather than descriptions of expert practice.

7. Cultural Embeddedness of Engineering. Karatas, Micklos, and Bodner (2011) state that engineering designs "are affected by cultural norms and the needs of society" (p. 125). While this statement conveys something important about engineering, the more important questions are *how* culture influences design, and *how* engineering design interfaces with society. Areas of interest include the ways that society provides inputs for engineering design, and the ways in which the outputs of design interact with society.

Complex technologies are often designed hierarchically, as a combination of systems and subsystems. While the subsystems are often negotiated by engineers, non-engineering social groups can strongly influence the design at the higher levels of the hierarchy (Constant, 1980; Vincenti, 1990). For instance, social groups strongly influence which problems a technology is meant to address, and what a given technology is "for." These issues are negotiated by many stakeholders, including the industrial organizations in which the technology is being developed, the eventual users of the technology, as well as the engineers designing the technology (Bucciarelli, 1994; Pinch & Bijker, 1987). The industrial firms that support design work are particularly crucial, as they provide the resources for design activities. Those resources can be increased or decreased for reasons that are informed only in part by the engineers. Firms are situated in larger social, economic, and political contexts, and these influences inevitably filter down to the design engineers who work within those firms (Bucciarelli, 1994).

How do the products of engineering interface with society? Technologies are the ultimate output of engineering, and so the question of how technology impacts society is of interest here. However, this issue is sufficiently broad that for the present purposes, the discussion will be narrowed only to what engineers most often consider. For one, engineers need to concern themselves with how to create technologies that are easily understood and used by operators—what are often called “human factors” (Norman, 2013; Vincenti, 1990). A growing interest exists in how technologies affect the behavior of their users, perhaps in undesirable or even dangerous ways (Carr, 2015; Turkle, 2012). Additionally, the field of professional engineering ethics addresses moral considerations of specific technologies (Florman, 1987; Latour, 1992; Mitcham, 1994). Most broadly, engineers must always consider the assumed want or need that their technological work is meant to address. Because engineers are rarely the users of the technologies they design, their work must operate on the assumption that some demand will exist for their designs. If demand does not currently exist, an assumption is often made that it *will* exist, but such assumptions are not always accurate, and some technologies are never adopted by their intended users (Banse & Grunwald, 2009; Callon, 1987; MacKenzie, 1987).

8. The Internal Culture of Engineering. Engineering takes place within a broader social context, but what are some of the cultural features of engineering itself? Some suggest that characteristically “engineering” ways of thinking and engaging with problems in the world exist (e.g., Florman, 1987, 1996). These ways of thinking can be located in the analytical methods that engineers employ, such as: breaking problems into hierarchical systems and subsystems, the use of estimation, or reduction of systems to abstract entities such as energy or force (Cross, 2000;

Hughes, 2004; Matthews, 1998; Vincenti, 1990). The use of reductionism within engineering is particularly emphasized within engineering education, but it is also a point of some controversy (Adams, 2004; Bucciarelli, 1994). Subdividing complex, real-world situations into abstract units is what allows engineers to draw upon abstract mathematical models or physical principles, and this has its advantages (Petroski, 1996; Simon, 1996). On the other hand, technological design demands that engineers attend to complexities inherent in the real world, as technologies don't exist only as abstractions. The tendency for engineers to engage with the world through reductionism can lead them to systematically ignore important aspects of technology, such as the experience of the user (Bucciarelli, 1994; Norman, 2013).

The tendency toward reductionism is but one aspect of engineering culture. Another more visible aspect is the high proportion of men in engineering, who make up 85% of the profession (NSF, 2017). The effects of this gender imbalance on workplace interactions have been well documented (Faulkner, 2009; Hatmaker, 2012). To what extent does this gender imbalance also affect the designs that engineers produce, or the research work they conduct? In what other ways do cultural characteristics of engineers affect their technological products?

Treated as a whole, engineering may have some unique characteristics, but many specializations exist within engineering, each of which have their own subcultures. Through their educational and professional experiences, engineers develop ways of representing the world in terms of abstractions and conceptual models (Dym & Brown, 2012). These representations vary between different engineering specializations; electrical engineers "see" the technological world in terms of currents and voltages, while mechanical engineers "see" technologies in terms of stresses and torques. Complex technological projects bring together engineers from a variety of backgrounds, as well as non-engineers, and these different ways of viewing the world must be continuously negotiated and resolved (Bucciarelli, 1994; Vincenti, 1990).

9. Engineering and Science. As is evident in several of the above features of engineering, the relationship between engineering and science is embedded in many facets of the engineering discipline. Overall, science is held in high esteem by the engineering community, as evidenced by the prominent role of science coursework during collegiate engineering education (Adams, 2004; Bucciarelli, 1994; Florman, 1987; Simon, 1996). Indeed, the association between modern engineering and science is often taken to be a distinctive feature of modern practice, separating it from the more crafts-based and artisanal approaches of the past (Florman, 1987; Petroski, 1996; Vincenti, 1990).

As was identified earlier, however, science and engineering are not identical. Scientific knowledge has utility for engineers, but is not sufficient to guide design work (Channell, 2009; Houkes, 2009; Kroes, 2012; Simon, 1996; Vincenti, 1990). Engineering science shares many characteristics with the natural sciences, but is directed towards different goals and thus uses different approaches (Banse & Grunwald, 2009; Mitcham & Schatzbeg, 2009; Petroski, 1996; Vincenti, 1990). Yet scientists and engineers often find themselves working side-by-side within technological organizations (Bucciarelli, 1994). What are the different roles that scientists and engineers play in technological activity? To what extent can their work be meaningfully disentangled in technological projects?

Summary of Features. The nine disciplinary features of engineering, resulting from the review of literature and discussed here, make clear many nuances and complexities inherent in the NOE. Understanding the NOE entails far more than being able to list or engage in practices that engineers employ; it demands understanding the kinds of work with which engineers engage, how engineers utilize and produce knowledge, the relationships between engineering and science, and the social environment that underlies all of these issues. Understanding the NOE means gaining a sense of the complexities underlying each of the features discussed above. The features cannot be reduced to a set of declarative statements, but rather are themes with which to engage and elaborate (Matthews, 2012). While nine features were addressed here, additional important features can likely be identified. The list is not meant to be exhaustive, but rather is intended to highlight some of the most frequently discussed NOE issues within the literature. Multiple ways exist to organize the list of disciplinary features, as they are all highly interrelated.

Context of Dissertation Studies

The context of the three studies presented here was a 4.5-year, NSF-funded STEM-C project (grant number 1440446) which aimed to improve the preparation of elementary teachers to teach science and engineering in a state that adopted NGSS. One part of the project involved placing a student teacher into a triad that included their cooperating teacher, and an engineering graduate student ('engineer' hereafter). The engineers spent one full day per week in the classroom over a 16-week semester, and all triads were situated in grade 3-5 classrooms in the same urban school district in the Midwest. The goals of the triads was to implement engaging science lessons with students and integrate engineering into the science instruction, when possible, while working within the boundaries of the district's existing science curriculum, and while fulfilling the university and state's requirements for multiple-subject student teaching. The Institutional Review Board (IRB) exempt approval form for the study is included as Appendix A.

Project participants were provided with a 2-day professional development workshop before the beginning of the semester, and a 1-day workshop midway through the semester.

During these workshops, participants experienced and reflected upon: a presentation by engineering faculty on the NOE, an inquiry-based science lesson utilizing the Learning Cycle approach (Lawson, Abraham, & Renner, 1989), and an engineering design activity following the *Engineering is Elementary* curricular materials (*EiE*; Museum of Science, Boston). Participants were also encouraged to consider the way that science and engineering can be meaningfully integrated in the elementary classroom, and were given time to begin planning for the semester.

While certain approaches to science and engineering instruction were modeled during the professional development workshops, the triads were not required to utilize any specific curriculum or lesson design when planning their lessons. The district had provided all schools with *FOSS* materials for their science program, but encouraged triads to deviate from them as desired in order to meet district and state science standards. Because of the novelty of engineering within elementary schools, *EiE* resources were made available to participants, and they were given a small budget for acquiring instructional materials, but they were not expected to use the *EiE* curriculum. Viewing engineering as a curriculum innovation, this professional development project was informed by McLaughlin's (1976) idea of *mutual adaptation*. In this perspective, teachers who successfully integrate engineering into the classroom are those who modify the innovation to their particular educational context. Because of these orientations of the professional development, most triads implemented engineering design activities that, while based on existing curriculum materials (including *EiE*, but others as well), were substantially modified by the triads for their contexts.

Also noteworthy is that, while triads most commonly used *design* activities for engineering instruction, this was not necessarily the only way that engineering was integrated into the classroom. Design activities are the most commonly advocated model of engineering instruction in elementary classrooms (Lachapelle & Cunningham, 2014; NAE & NRC, 2009; NRC, 2014), and are very common in elementary curricular materials (e.g., *EiE, FOSS, TeachEngineering.org*). Engaging students in engineering design activities, however, is not the only way to teach students about engineering. This point was raised during the professional development workshops, and participants were encouraged to explore other modes of engineering instruction.

Overview of Dissertation Studies

This dissertation is organized into five chapters and contains three papers that relate to the NOE within elementary engineering education. Chapter 1 provides background on K-12 engineering efforts, situates the NOE as a learning objective within those efforts, and gives a detailed description of the NOE construct. Chapters 2-4 each contain a single research study related to the NOE. Chapter 5 summarizes the major findings from those studies, identifies relationships between those findings, and puts forth a set of overall results and implications.

The first research study, included as Chapter 2, investigates elementary teachers' understanding of a key aspect of the NOE (the "Scope of Engineering") before and after participating in the STEM-C project. If teachers are to accurately communicate the NOE to students during engineering instruction, they must be knowledgeable about the NOE. Prior research studies indicate that some elementary teachers hold misconceptions about the NOE, but they provide few details about those misconceptions, or the extent to which they can be addressed. A significant component of this study is the refinement of an instrument that can be used to assess teachers' knowledge of the "Scope of Engineering."

The second research study, included as Chapter 3, investigates how elementary teachers view their students' learning about engineering: which learning outcomes they consider, and which they do not. Of particular interest is the extent to which teachers describe students' learning of the NOE as an important outcome of engineering design activities. NOS research has indicated that NOS often is not prioritized by teachers, and when it is not prioritized, it is not addressed with students (Herman, Clough, & Olson, 2013, 2017; Lederman, 1999). Similarly, if teachers do not prioritize the NOE as a learning outcome, they are unlikely to address the NOE with their students.

The third research study, included as Chapter 4, examines the engineering teaching practices of elementary teachers, and explores the ways that they explicitly and implicitly convey the NOE to students. Some prior work has examined teachers' engineering teaching practices in general (e.g., Capobianco & Rupp, 2014; Dare, Ellis, & Roehrig, 2018), but none have examined how the NOE is taught during engineering instruction. Using multiple case study methodology, this study provides an in-depth look at how five triads taught the NOE over the course of a semester. Analyses focus not only on how the NOE was communicated during engineering lessons, but also the extent to which triads attended to the NOE during planning and when reflecting on lessons and student learning.

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CHAPTER 2. THE DEVELOPMENT OF ELEMENTARY TEACHERS' KNOWLEDGE OF THE SCOPE OF ENGINEERING

Abstract

As engineering becomes an increasingly prominent part of science standards and curricula, an important question is how best to prepare teachers for this subject area. This preparation necessarily entails developing teachers' knowledge of engineering, and one important component of engineering knowledge is the nature of engineering (NOE). Like the nature of science (NOS), the NOE describes the work of engineers, the epistemological underpinnings of engineering, and the relationships between engineering and other fields of study. The present study describes a quantitative measure that was developed for assessing teachers' knowledge of a particular NOE dimension: the scope of engineering (SOE), which describes what does and does not fall under the umbrella of engineering work. This measure was then used to assess the SOE knowledge growth of participants in a research project focused on improving elementary science and engineering education. Participants included elementary student teachers, cooperating teachers, and engineering graduate students who were teamed with the teachers. Results indicate that the SOE knowledge of all participants, including the engineering graduate students, improved over the course of the project. Recommendations for future use of the SOE measure are described, alongside promising avenues for future instrument development.

Introduction

Engineering is increasingly becoming a part of science standards and curricula across the United States. The Next Generation Science Standards (NGSS Lead States, 2013) place substantial emphasis on engineering, and many states have adopted their own engineering standards (Moore et al., 2015). As engineering enters science curricula and classrooms, a significant challenge lies in preparing teachers to address this novel subject. Many teachers, especially at the elementary level, have limited preparation in engineering (Banilower at al., 2013), and lack deep knowledge of the subject (Hsu, Purzer, & Cardella, 2011). Given the importance of teacher knowledge for effective instruction (Ball, Thames, & Phelps, 2008; Bell, 2005; Gess-Newsome, 1999; Shulman, 1986), developing teachers' engineering knowledge is a key task for K-12 engineering education efforts.

While some disagreements exist regarding the engineering concepts that are relevant for K-12 education (Custer, Daugherty, & Meyer, 2010; NAE, 2010), many points of consensus do exist. Understanding engineering design, and the skills associated with it, is often regarded as a crucial element of engineering knowledge (Brophy, Klein, Postmore, & Rogers, 2008; Cunningham & Carlsen, 2014; Katehi, Pearson, & Feder, 2009; Sidawi, 2009). Another important set of ideas relate to the *nature of engineering* (NOE): what engineering is, what engineers do, engineering's relationship with other disciplines, and its relationship with society (Cardella, Salzman, Purzer, & Strobel, 2014; Lachapelle & Cunningham, 2014; NAE & NRC, 2008, 2010; NRC, 2014). Knowledge of certain NOE aspects has been an area of research interest at the elementary level, where misconceptions have been documented in teachers and students (Capobianco et al., 2011; Cunningham, Lachapelle, & Lindgren-Streicher, 2005, 2006; 2014; Lambert et al., 2007; Montfort, Brown, & Whritenour, 2013). While these studies make clear that elementary teachers' and students' NOE knowledge needs to be improved, the work in this area has been mostly exploratory. The NOE is multidimensional (see Chapter 1), but the above studies are not clearly tied to any specific dimensions, nor do they use instruments that are tailored to specific aspects of the NOE. Some studies suggest that teachers' NOE views can be positively impacted by professional development (e.g., High et al., 2009; Hoh, 2012), but the specific areas in which teachers' NOE knowledge develops is unclear.

The present study provides a more targeted examination of elementary teachers' NOE knowledge by focusing on a specific NOE dimension: the "Scope of Engineering" (SOE, see Chapter 1), which address what does and does not fall into the domain of engineering work. The present work assesses elementary teachers' SOE knowledge before and after participating in a professional development project aimed at supporting elementary engineering instruction. As part of this project, elementary teachers were supported by engineering graduate students who regularly visited their classrooms. As no good instrument yet exists for measuring the SOE construct, a key goal of this study was developing an instrument to measure knowledge of the SOE. The study was guided by the following research questions:

1) How can project participants' SOE knowledge be measured?
2) What differences, if any, exist in teachers' knowledge of the scope of engineering before and after participation in this project?
3) How do the teachers compare to the engineers in terms of scope of engineering knowledge before and after participation?

Theoretical Framework – Defining the SOE Construct

Engineering is fundamentally concerned with technology, but not all technological work is engineering. Many K-12 students think engineers fix cars or operate machinery (Chou & Chen, 2017; Cunningham, Lachapelle, & Lindgren-Streicher, 2005; Fralick, Kearn, Thompson,

& Lyons, 2009; Weber, Duncan, Dyehouse, Strobel, & Diefes-Dux, 2011), and though these are technological activities, they are not *engineering* activities. Fixing cars and driving forklifts are relatively unambiguous cases of non-engineering, but not all technological activities are necessarily as easily categorized. Engineers are responsible for a wide variety of technological work (Mitcham & Schatzberg, 2009), and although engineering is often primarily associated with technological design (e.g., Dym et al., 2005; NRC, 2012), engineers are also involved with research (Channell, 2009; Petroski, 1996; Vincenti, 1990), investigating technological failures (Matthews, 1998), overseeing technological projects (Florman, 1987), and even certain maintenance activities (Mitcham, 1994). Given the wide range of engineering work, how can a clear sense of the SOE be obtained?

Conceptually, the SOE involves the issue of demarcation: what counts as engineering and what does not. To better understand the demarcation question in engineering, the issue of demarcation in science provides a useful example. Because scientific knowledge occupies a privileged position in our society, philosophers have tried to distinguish science from non-science for over a century. Past philosophical efforts typically focused on identifying essential characteristics of scientific knowledge that make it fundamentally different from other knowledge forms, including pseudo-sciences like astrology (Laudan, 1983; Pigliucci, 2013; Popper, 1959/1972). Yet despite extensive philosophical work on demarcation, Laudan declared that philosophers have "largely failed to deliver the relevant goods" (1983, p. 111); no necessary or sufficient criteria have yet been developed that adequately separate science from non-science.

Although the state of the demarcation problem in the philosophy of science might not seem encouraging, room for optimism remains. Pigliucci (2013) points out that, while past endeavors have been unsuccessful, this does not necessary imply that demarcation is impossible.

While no distinct line separates science from non-science, Pigliucci argues that ways exist to indicate the degree to which a field of study is more, or less, scientific. The family resemblances approach of Wittgenstein (1953) holds considerable promise in this regard (Dupré, 1995); the different sciences are not defined by a set of essential characteristics, but nevertheless cohere together through a network of relations. Even though such a view can only provide fuzzy boundaries for science, many unambiguous and generally-agreed-upon cases of genuine science and non-science can nevertheless be identified (Pigliucci, 2013).

Taking some lessons from the challenge of demarcation in science, necessary or sufficient criteria that clearly separate engineering from other technology-related fields are unlikely to be easily stated, if they exist at all. While unambiguous cases of non-engineering can be identified, such as that of a car mechanic, a list of essential characteristics that separate the mechanic from the engineer cannot be stated. Furthermore, borderline cases exist that are difficult to categorize. As mentioned above, many engineers supervise technological projects, especially in the case of civil engineering (Florman, 1987). But does this necessarily mean that all supervisors of technological projects are acting as engineers? Even broad definitions of engineering (e.g., NRC, 2012) rarely, if ever, include supervision. Given the diverse set of activities with which engineers are involved, a family resemblances approach is likely to be the most fruitful for defining the SOE.

While fully elaborating the family resemblances of engineering is beyond the scope of this paper, several distinctions can be put forth that help give a sense of the SOE. These distinctions should not be taken to be unambiguous separations between engineering and non-engineering, but rather as indications of what makes certain activities more (or less) like engineering. Many (although not all) engineers are involved with the design and development of novel technologies (Dym et al., 2005; Petroski, 1996; Vincenti, 1990). In contrast, engineers are less involved in carrying out the production of technologies, or in their use (Dym & Brown, 2012; Kroes, 2012; Vincenti, 1990). Engineers can also engage in research, and while this research borrows many of the methods of the natural sciences, it is focused on technological phenomena (Banse & Grunwald, 2009; Mitcham & Schatzbeg, 2009). Engineers also frequently conduct analyses of existing or planned technologies, often utilizing theoretical ideas from science (Bucciarelli, 1994; Dym & Brown, 2012). The analytical character of engineering work is unlike crafts-based or artisanal approaches to technological design (Petroski, 1996; Vincenti, 1990).

Based on the distinctions described above, one way to describe the SOE is to place various technological activities on a spectrum, ranging from “more like engineering” to “less like engineering.” Figure 2.1 provides one such spectrum, and does not identify a bright line separating engineering from non-engineering. Rather, certain activities are considered closer or more distant from engineering practice. Repairing a device such as a car, for example, is more distant from the work of engineering, as it does not typically entail the design of cars, nor theoretical analyses or investigations of automobile systems. A more ambiguous activity, located in the middle of the spectrum, is that of overseeing a technological project, such as the construction of a bridge. In itself, supervising bridge construction does not resemble engineering, but if the overseer had also been involved in the design of the bridge, or was conducting analyses of the bridge as it was being built, then greater resemblance would be shown.

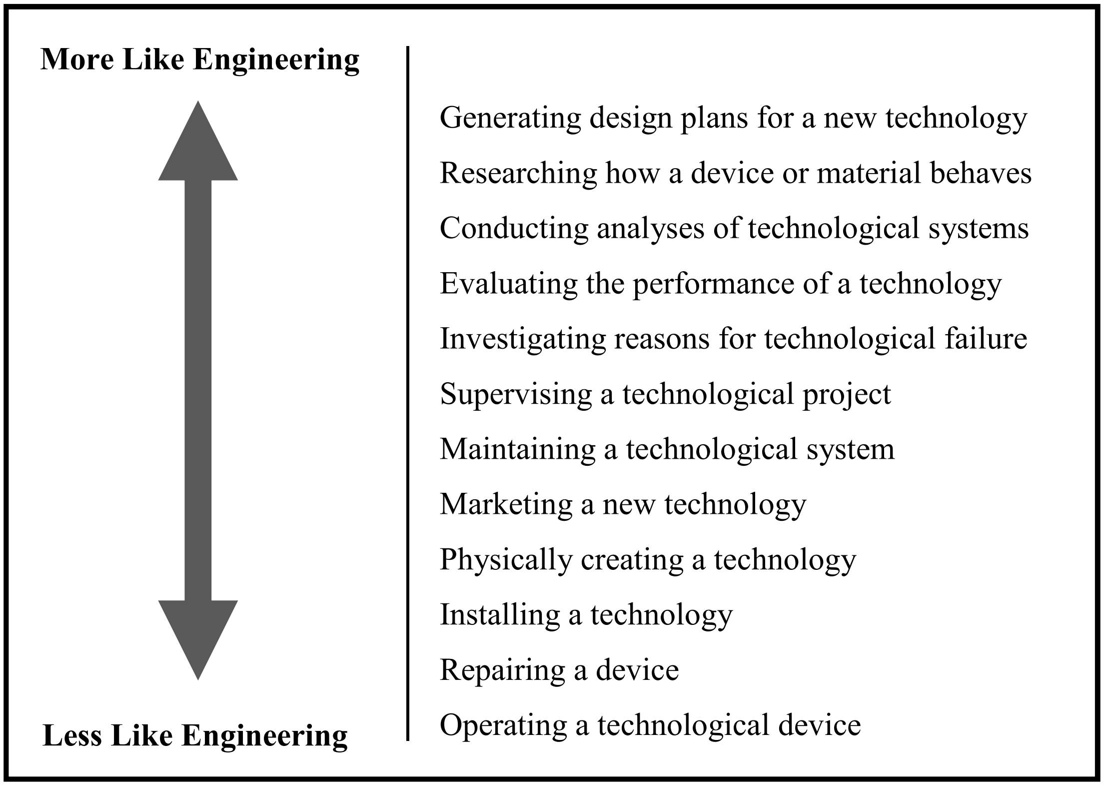

Figure 2.1: Resemblance of Different Technological Activities to Engineering

A family resemblances approach to defining the SOE makes sense for philosophical reasons, but the approach has merit for other reasons as well. The family resemblances approach has many similarities to the semantic network models that are commonly used to describe how words are stored in people's internal lexicons. For example, in spreading activation models of semantic networks (Bock & Levelt, 1994; Collins & Loftus, 1975), words and concepts are organized in a web of interconnecting nodes that are similar in many ways to features of family resemblance. So not only is the family resemblances approach philosophically appealing, but it can also be used to describe how people think about terms like "engineering". This has implications for how SOE knowledge ought to be assessed, an issue which is discussed in more detail below.

Literature Review

Although the "SOE" nomenclature has not been used, many prior studies have identified gaps in teachers' and students' SOE knowledge (Cunningham, Lachapelle, & Lindgren-Streicher, 2005, 2006; Fralick, Kearn, Thompson, & Lyons, 2009; Weber, Duncan, Dyehouse, Strobel, & Diefes-Dux, 2011). One reason why SOE knowledge is important for students is that many K-12 engineering efforts seek to generate students' interest in engineering as a career pathway (Brophy et al., 2005; NRC, 2012). Promoting genuine student interest in engineering requires that those students understand what engineering is and is not (i.e., the SOE); students who are interested in engineering based on erroneous understandings of the discipline will not be well served. Understanding the SOE also contributes to students' ability to distinguish science and engineering, which is especially important given that engineering is often incorporated into science instruction, and concerns have been raised about potential conflation of these two disciplines (McComas & Nouri, 2016).

One method that has often been used to investigate students' knowledge of the SOE is the Draw-An-Engineer-Test (DAET, Knight & Cunningham, 2004). The DAET tasks the respondent with drawing "an engineer doing engineering work" and provides a space for the respondent to write about what the engineer is doing. Studies of elementary and middle school students' drawings have indicated that students do not have well-developed ideas about what engineers do. Students' drawings often show engineers repairing engines, doing construction work, or engaging in other skilled-labor tasks that fall outside the range of engineering work (Capobianco, Diefes-Dux, Mena, & Weller, 2011; Chou & Chen, 2017; Fralick, Kearn, Thompson, & Lyons, 2009; Rynearson, 2016; Weber et al., 2011). A different open-ended prompt that has also been used to assess SOE views is to ask respondents: "What is engineering?" and "What do engineers do?" Like the findings from the DAET, studies that have used this approach have similarly found evidence of misconceptions about the SOE among elementary students and teachers (Cunningham, Lachapelle, & Lindgren-Streicher, 2005, 2006; Lambert et al., 2007). Yet while these open-ended approaches have revealed misconceptions about the SOE, a significant limitation is that these methods do not directly elicit respondents' SOE thinking. Further, when participants produce single drawings or definitions of engineering, they are unlikely to convey their full range of thinking about the SOE.

A more direct approach to assessing SOE views is to task participants with categorizing various activities as either engineering or non-engineering. Cunningham, Lachapelle, and Lindgren-Streicher (2005, 2006) gave elementary students and teachers a categorization task and found that, while teachers performed better than students, both groups frequently made inaccurate categorizations. Over half of the teachers, for example, indicated that engineers install wiring, repair cars, and drive machines as part of their jobs. In a later study, they found that elementary students' categorizations were improved after completing an *Engineering is Elementary* (EiE; Museum of Science, Boston) unit (Cunningham & Lachapelle, 2007). A similar version of the activity-categorization task was also used by Hammack, Ivey, Utley, and High (2015) to investigate the views of middle school students who participated in an engineering summer camp. They also found evidence of misconception views in their students, and these were only slightly improved over the course of the summer camp. Ozogul, Miller, and Reisslein (2017) used a different categorization task with K-5 students and also found evidence of misconception views, although they also found that older students tended to have fewer misconceptions than younger students.

Interviews can also be used to assess participants' SOE views. Montfort, Brown, and Whritenour (2013) interviewed high school students about a range of NOE topics that included the SOE. They found that, while about half of the interviewed students accurately associated engineering with designing and planning activities, most students also indicated that engineers are involved with "the mechanistic work of building and fixing" (p. 7). Regardless of the method, the results found by the studies discussed here is much the same: elementary teachers and students at all grade levels hold inaccurate views about the SOE. SOE misconceptions take the form of overbroad notions of engineering work. Participants in the above studies often accurately associated engineering with the design of technology, but they also inaccurately identified maintenance, repair, or construction work as engineering.

While the above studies all investigated participants understanding of the SOE, they did not use consistent terms to describe what was being investigated. Some studies investigated participants' "conceptions of engineering" (e.g., Capobianco et al., 2011; Cunningham, Lachapelle, & Lindgren-Streicher, 2006), one investigated their "understandings of the concept of *engineering*" (Montfort, Brown, & Whritenour, p.6, emphasis in original), another their "actual knowledge of engineering occupational activities" (Ozogul, Miller, & Reisslein, 2017, p. 19). Two issues emerge from this array of terminology. The first is a communication issue; if the "SOE" were identified as the construct that ties these studies together, the results of these studies could be more clearly compared. Second, and more importantly, the studies tended to use terms that encompassed more than the SOE; "conceptions of engineering," for instance, might include not only the SOE, but the relationship between engineering and science, or the cultural embeddedness of engineering. As a result of this second issue, many of the studies that investigated the SOE did not use instruments that tightly aligned to the construct. The DAET, for example, is not specifically designed to elicit respondents' SOE views. The categorization tasks used in several studies were more closely aligned to the SOE, but as is discussed below, even these tasks can be problematic in this regard.

In summary, studies that have investigated participants' SOE knowledge have consistently found evidence of misconceptions in students and teachers, and some evidence is emerging that these misconceptions can be addressed via instruction. However, a significant need exists to utilize consistent terminology in relation to the SOE, and to refine research methods so that they are tailored specifically to the SOE construct. If a research goal is to determine how to effectively improve students' and teachers' SOE knowledge, or any other NOE dimension, then research instruments that are highly aligned to well-defined constructs are essential (NRC, 2001).

Methods

Study Context

This study took place within the context of an NSF-funded professional development and teacher education project focused on improving elementary teacher preparation for science and engineering instruction (described in more detail in Chapter 1). One component of the project is a 16 week student teaching experience that placed a student teacher in a triad with a cooperating teacher and an engineering graduate student ("engineer") who worked together to plan and implement science and engineering lessons is grades 3-5 classrooms. Project participants all worked in classrooms in a large urban school district that serves a diverse student population. The engineers attended the elementary classroom one full day per week and received ongoing support by attending a one-hour per week course on campus with project staff. Triads' classrooms were visited every other week by project research staff to conduct observations and provide instructional and organizational support.

Project participants completed multiple professional development workshops, summarized in Table 2.1, each of which addressed aspects of effective science and engineering instruction. Of most relevance to the present study, workshop 2 explicitly addressed ideas related to the NOE for approximately 45 minutes. The NOE was communicated via a presentation that targeted the following ideas: the various jobs that people with engineering degrees might hold after graduation, how design engineers consider criteria and constraints in their work, and the ways that scientific knowledge has impacted engineering and technology.

Table 2.1: Descriptions of Project Workshops

	Timing	Participants	Topics
Workshop 1	3 days prior to beginning semester	Engineers	-Legal issues of working in schools, and the engineers' roles in the classroom -Elementary student cognition, learning -Effective science and engineering instruction
Workshop 2	2 days, directly after Workshop 1	Engineers Cooperating teachers Student teachers	-Effective science and engineering lessons modeled for participants -Integrating science, math, and engineering instruction -The nature of engineering (NOE) -Co-teaching strategies -How to work and plan as a team
Workshop 3	1 day, middle of the semester	Cooperating teachers Student teachers	-Effective science and engineering lessons modeled for participants

In addition to the workshops, the professional development model used in the present study also treated teachers' classrooms as important sites for teacher learning (Grossman, Smagorinsky, & Valencia, 1999; Morine-Dershimer, 1989). The role of the engineers in these classrooms was critical in this regard. Cooperating teachers and student teachers can potentially develop their engineering knowledge, including knowledge of the NOE, through the act of teaching the subject (Arzi & White, 2008; Nixon, Hill, & Luft, 2017; Van Driel, Berry, & Meirink, 2014). But given the teachers' limited preparation in engineering (Banilower et al., 2013), learning through teaching was unlikely to be successful without considerable support. By serving as engineering content experts, the engineers in this study could facilitate the teachers' learning of engineering as the triads planned and implemented lessons as a team.

Underlying this hypothesis regarding the impact of the triad structure on teacher knowledge is the assumption that the engineers have relatively expert NOE knowledge when compared to teachers. The engineers were undoubtedly more expert within their areas of engineering specialization, but the case of NOE knowledge is less clear. Studies of scientists have found that, while their nature of science (NOS) views are generally more informed than that of science teachers and students, they are not necessarily consistent with the desired state (Glasson & Bentley, 2000; Schwartz & Lederman, 2008; Yore, Hand, & Florence, 2004). Similarly, engineers, particularly graduate students, may not necessarily hold completely informed NOE views. Testing the assumption that engineers have well-developed NOE views was therefore an important consideration for the present study.

Participants and Data Collection

Data for the present study come from the first six semesters of data collection for the project (Fall 2015-Spring 2018). Each semester, ten student teacher/cooperating teacher/engineer triads participated in the project; while student teachers and cooperating teachers participated for only a single semester, engineers participated for an entire year. A SOE survey (described below) was administered to all participants before the beginning of the semester and at the end of their participation. Because the engineers participated for an entire year, they completed this survey three times: prior to participation, after their first semester, and after their second semester. More than a pretest and posttest survey were also obtained for nine cooperating teachers and two engineers who participated in the project twice. In all following analyses, except for the analysis of the triad structure, only the pretest and posttest data from a participant's first semester of participation were used. In total, 60 student teachers, 51 cooperating teachers, and 28 engineers comprise the treatment group sample for the study.

A control group was also recruited for the study, consisting of 40 pairs of student teachers from the same teacher education program and their cooperating teachers. They taught the same grade levels and in the same geographic region as the treatment group, although school districts also included suburban and rural areas in addition to urban ones. While treatment group participants completed surveys as pre- and posttests, control group participants completed them as posttests only. One control group cooperating teacher did not complete the survey for the present study. Data from the control group were used only for the purposes of analyzing the psychometric properties of the instruments used in the study.

Instrument Construction

Item Selection. Investigating participants' SOE knowledge requires an instrument that is highly aligned to the construct (NRC, 2001), but as discussed above, many of the available instruments that tap NOE knowledge are not highly aligned to the SOE. One promising instrument for assessing SOE knowledge is the "What is Engineering?" (WE) survey, developed by *Engineering is Elementary* (Museum of Science, Boston) and included as Appendix B. The survey was initially created for use with elementary students (Cunningham, Lachapelle, & Lindgren-Streicher, 2005), but has also been administered to teachers (Cunningham, Lachapelle, & Lindgren-Streicher, 2006). Since its development, the survey has been expanded and revised, and the form used for the present study consisted of three questions:

a. An open-ended question that asks: "What is an engineer?"
b. Respondents select from a list of 37 activities examples of things an engineer might do, such as: "Develop smaller cell phones" or "Repair cars"

c. Respondents rate on a Likert-type scale the importance of 21 activities to an engineer, such as: “Driving machines” or “Solving problems”

The three items are aligned to the SOE construct to varying extents, but only those that are highly aligned ought to be used to assess SOE knowledge (NRC, 2001).

Question (a), the open-ended item “What is an engineer?”, has the potential to elicit ideas related to the SOE, but it is also likely to elicit ideas that relate to other NOE dimensions. More importantly, responses to this question may not address the SOE at all (e.g., the common response, “engineers solve problems,” does not clearly convey anything about the SOE). For this reason, the first question was not used to assess participants’ SOE knowledge.

Question (b) appears to be closely related to the SOE. The task of categorizing various activities as things that engineers might or might not do appears highly related to the SOE construct. The drawback of this question lies in the dichotomous nature of the task. If a family resemblances perspective is taken for the SOE, the most appropriate question is not whether an activity definitively is or is not engineering, but the extent to which it is *like* engineering (see Figure 2.1). A dichotomous question forces respondents to sharply differentiate activities that may only differ in their relationship to engineering work by degrees, thus producing a threat to validity. Furthermore, respondents might choose to place the dividing line between engineering and non-engineering in idiosyncratic ways. For instance, a respondent might identify “fixing computers” as something an engineer would do not because it is activity that is *highly* like engineering, but because it is at least *somewhat* like engineering.

Question (c) has a potential advantage over question (b) in that participants can rate activities as more or less important to engineers. This kind of task is more in line with the family resemblances approach to characterizing the SOE. To further investigate this potential advantage, and the possible issues with question (b), cognitive interviews (Willis, 2004) were conducted with a sample of ten project participants, all of whom were cooperating teachers or student teachers. The cognitive interview questions focused on how respondents decided to categorize the activities in questions (b) and (c), and participants' responses were transcribed and analyzed with respect to their patterns of reasoning.

When answering question (b), most respondents stated that all the activities *could* be done by engineers, but that some were more likely to be done than others. Most respondents chose to only select the "likely" items from the list, but some selected all the activities because they could see some potential connection between each one and engineering. Respondents reported similar patterns of reasoning for question (c): most viewed certain activities and skills as more relevant to engineering than others, while acknowledging that all of the activities could *potentially* be linked to engineering. Unlike question (b), however, no respondents rated all of the items equally highly on the Likert-type scale; those items that were only *potentially* related to engineering were rated lower than the others. Based on the responses to the cognitive interviews and the arguments above, the format of question (c) is best suited to assessing SOE knowledge, and was therefore used in subsequent analyses.

However, not all of the items within question (c) relate directly to the SOE construct. For example, rating the importance of "using their creativity" to engineers does not likely tap participants' SOE knowledge. While creativity might form a part of a family resemblances picture of engineering, essentially all human work involves creativity to some degree. "Brainstorming different ideas" is another item that appears to have only weak connections to the SOE. Participants' thinking about this item likely relates more to their ideas about what engineering design entails, rather than issues of demarcation. Thus, additional analysis and refinement of question (c) was needed to make it appropriate for targeting the SOE construct. Presented below is an approach to scoring this question in a way that generates a "Scope of Engineering Subscale" (SOE-S) which is highly aligned to the construct. The analysis used to generate the SOE-S utilized pretest data from project participants along with data collected from the control group (n = 226).

Development of SOE-S Question (c) asks participants how important a set of 21 different activities are to the work of an engineer. Participants used a Likert-type scale to rate each item from 1 (not important) to 5 (very important). Of 21 activities, the 14 considered to be associated with engineering, such as "using models" and "testing ideas," were labeled as "accurate." The remaining 7 activities, labeled "inaccurate," represent activities that are far removed from engineering work, such as "using power tools to build things" and "driving machines." Whether the items were considered accurate or inaccurate was determined by the developers of the survey by giving the items to a sample of engineers. Prior to analyzing these items, responses for the 7 "inaccurate" items were reversed, as correct responses for these items would rate them as "1" (not important to the work of an engineer). Table 2.2 provides descriptive statistics for all 21 items.

Table 2.2: Descriptive Statistics for Question (c) Items (n=226)

SOE-S Item (*Denotes "Inaccurate" Item)	Mean (out of 5) (*Item Scores Reversed)	Standard Deviation
Using math	4.84	0.41
Using models	4.68	0.58
Testing ideas	4.90	0.36
Working as a team	4.75	0.53
Doing experiments	4.59	0.73
Solving problems	4.92	0.30
Sketching ideas	4.58	0.70
Using their creativity	4.85	0.40
Understanding science	4.75	0.52
Reading about inventions	4.08	0.90
Writing down their ideas	4.57	0.63
Writing reports for other engineers	3.92	1.09

Table 2.2 continued

Brainstorming different ideas	4.82	0.41
Telling other people what they found out	4.44	0.83
*Driving machines	3.45	1.13
*Building houses	3.63	1.21
*Repairing engines	3.41	1.22
*Using power tools to fix things	3.20	1.14
*Using power tools to build things	3.01	1.16
*Fixing broken things for other people	3.09	1.24
*Driving people from place to place	4.34	0.98

Examination of the 21 items in Table 2.2 reveals several issues. First, many of the "accurate" items show near-ceiling performance, with correspondingly low standard deviations. Such items offer little capacity to discriminate participants' SOE knowledge, let alone assess knowledge growth (DeVellis, 2003). The near-ceiling performance on the "accurate" items is not necessarily surprising, as prior research has shown that inaccurate SOE views are typically those of over-permissiveness, wherein too many activities are categorized as engineering rather than too few (Cunningham, Lachapelle, & Lindgren-Streicher, 2005, 2006; 2014; Lambert et al., 2007). A more important issue is that some of the 21 items are not aligned with the SOE construct. For instance, while respondents' views on the importance of "Understanding science" to engineers is related to the NOE in general, it is not an SOE issue. The same is true for many of the "accurate" items, including "Working as a team" and "Using their creativity." Finally, the co-presence of "accurate" and "inaccurate" items means that combining all items into a single scale score is not necessarily appropriate. Even after reversing the ratings for the "inaccurate" items, they may not function similarly to the "accurate" ones (Barnette, 2000).

To investigate further, the internal reliability of the items were calculated. Cronbach's α based on standardized items for the 21 items was 0.753, which is acceptable, but not as high as desired (DeVellis, 2003). More troublingly, the mean inter-item correlation was 0.127, ranging from -0.403 to 0.860, which provides evidence that the items do not all cohere into a single scale.

To further investigate this possibility, a principal components factor analysis (PCA) was conducted using SPSS version 24. The Kaiser-Meyer-Olkin measure for these data was 0.860, exceeding the recommended value of 0.6 (Kaiser & Rice,1974), and Bartlett's Test of Sphericity (Bartlett, 1954) was statistically significant at $p<0.001$, indicating that these data were suitable for factor analysis.

Exploratory PCA revealed four components with eigenvalues greater than 1, explaining 26.5%, 17.3%, 6.1%, and 5.9% of the variance respectively. The screeplot of the four components showed a clear break after the first two, and thus only they were retained for further investigation (Cattell, 1966). The two-component solution explained 43.8% of the total variance. Using an oblimin rotation solution, a simple structure was found such that both components loaded strongly on multiple items, and nearly all items strongly loaded on only one component (Thurstone, 1947). The varimax solution produced nearly identical results. The pattern matrix, structure matrix, and communalities for these items are given in Table 2.3. These results support the separation of this survey into two separate subscales.

As expected, the factor analysis separated the "accurate" from the "inaccurate" items. The subscale formed by the "inaccurate" items is promising in that the items are clearly related to the SOE. The coherence of the seven "inaccurate" items is indicated by their Cronbach's α statistic of 0.899, a nearly optimal value (DeVellis, 2003). In addition, the mean inter-item correlation of the seven items was 0.561, ranging from 0.425 to 0.862, indicating high coherence among the items. The corrected item-total correlations, shown in Table 2.4, were also high for this group of items, providing further evidence of their high internal reliability.

Table 2.3: Pattern and Structure Matrix for PCA with Oblimin Rotation

Item	Pattern Coefficients		Structure Coefficients		Communalities
	Component 1	Component 2	Component 1	Component 2	
Brainstorming different ideas	**0.720**	0.118	**0.700**	-0.005	0.503
Writing down their ideas	**0.706**	0.050	**0.697**	-0.070	0.489
Using their creativity	**0.601**	0.063	**0.591**	-0.039	0.353
Sketching ideas	**0.601**	0.075	**0.589**	-0.027	0.352
Testing ideas	**0.572**	0.184	**0.541**	0.086	0.325
Reading about inventions	**0.566**	**-0.303**	**0.618**	**-0.400**	0.471
Solving problems	**0.556**	0.223	**0.518**	0.128	0.317
Telling other people what they find out	**0.549**	-0.046	**0.557**	-0.140	0.313
Using models	**0.548**	-0.058	**0.558**	-0.151	0.314
Understanding science	**0.537**	-0.077	**0.550**	-0.168	0.308
Working as a team	**0.526**	-0.182	**0.557**	-0.272	0.343
Doing experiments	**0.507**	-0.122	**0.528**	-0.209	0.293
Writing reports for other engineers	**0.461**	-0.104	**0.479**	-0.182	0.240
Using math	**0.426**	-0.101	**0.443**	-0.174	0.206
Using power tools to fix things	-0.037	**0.867**	-0.185	**0.874**	0.765
Repairing engines	-0.044	**0.847**	-0.188	**0.854**	0.732
Building houses	0.077	**0.808**	-0.060	**0.795**	0.637
Using power tools to build things	-0.096	**0.806**	-0.233	**0.823**	0.686
Driving machines	0.021	**0.746**	-0.106	**0.742**	0.552
Fixing broken things for other people	-0.116	**0.710**	-0.236	**0.729**	0.545
Driving people from place to place	0.070	**0.676**	-0.045	**0.664**	0.445

Note: major loadings for each item are in bold.

Table 2.4: Corrected Item-Total Correlations of the Seven "Inaccurate" Items

SOE-S Item	Corrected Item-Total Correlation
Driving machines	0.648
Building houses	0.700
Repairing engines	0.792
Using power tools to fix things	0.824
Using power tools to build things	0.748
Fixing broken things for other people	0.658
Driving people from place to place	0.576

In contrast, the subscale formed by the fourteen “accurate” items did not show high internal reliability. This was reflected by the relatively lower communalities in Table 2.3, relative to the subscale formed by the “inaccurate” items. Cronbach’s α for these items was 0.838, which is reasonable (DeVellis, 2003); however, the mean inter-item correlation was 0.270, ranging from 0.063 to 0.473, which does not show high coherence among the items. The corrected item-total correlations for the “accurate” items subscale, shown in Table 2.5, are also far less than those of the “inaccurate” items subscale.

Table 2.5: Corrected Item-Total Correlations of the Fourteen “Accurate” Items

Item	Corrected Item-Total Correlation
Using math	0.364
Using models	0.485
Testing ideas	0.409
Working as a team	0.469
Doing experiments	0.399
Solving problems	0.373
Sketching ideas	0.470
Using their creativity	0.451
Understanding science	0.469
Reading about inventions	0.556
Writing down their ideas	0.599
Writing reports for other engineers	0.424
Brainstorming different ideas	0.578
Telling other people what they found out	0.490

Based on these analyses, the seven “inaccurate” items were separated from the “accurate” ones, and only the “inaccurate” items were used for the “Scope of Engineering Subscale” (SOE-S). The “accurate” items were not used in further analysis because they showed sufficient issues to prohibit further use, including:

-Several of the items do not appear related to the SOE (e.g., “Using their creativity” and “Working as a team”)

-Among the items that are potentially related to the SOE, many are vague (e.g., "Sketching ideas" and "Writing down their ideas")

-Most of the items show a ceiling effect (see Table 2.2)

-The internal reliability of the items does not indicate a coherent subscale

Because the SOE-S developed here contained only inaccurate items, it was considered a *misconception* scale; the SOE-S indicates the presence of *inaccurate* views rather than *accurate* ones. This was not considered problematic, however, as prior research indicates that less-informed SOE views tend to be those in which too many activities are associated with engineering, rather than too few (Cunningham, Lachapelle, & Lindgren-Streicher, 2005, 2006; 2014; Lambert et al., 2007).

Results

To investigate how project participants' understanding of the SOE changed over the course of the project, the 7-item SOE-S described above was used to assess participants' SOE knowledge on the pretest and posttest. These data come from the same pool of participants as the reliability and factor analysis data above, but in this case data were only used from participants who completed both the pretest and posttest. This requirement excluded the control group from analysis, along with a small group of treatment participants who either did not complete the study or did not complete the survey. For this analysis, 49 cooperating teachers, 59 student teachers, and 28 engineers comprise the sample.

Potential Influence of Triad Structure

A complexity introduced into the data set is due to the triad structure of the project. While the project was structured similarly for all participants, the experiences of the three members of a given triad were *most* similar to each other's. For this reason, triad members could not be assumed to be independent, and their SOE-S scores might have developed similarly from the beginning to the end of the semester. To determine whether this was the case, SOE-S gain scores were calculated for each participant by subtracting their pretest from posttest scores. For the purposes of this analysis only, engineers' data from both semesters of participation were used, with a gain score calculated for each semester. The variability of these gain scores was then calculated within each triad for a given semester of data collection.

For each semester of data collected, the within-triad SOE-S gain score variance was calculated, and then summed across all ten triads. If membership in a particular triad influences SOE-S score gains, then this total variance should be *lower* than would be expected if participants were not related via triads. To test this possibility, a bootstrapping method of resampling was employed (Efron, 2003) to generate an empirical distribution of total within-triad SOE-S gain score variances. For each semester of data collection, all participants were randomly reassigned to new triads, and the total within-triad SOE-S gain score variance was calculated for each of 10^5 iterations of reassignment. The observed total within-triad variances for each semester were then compared to the empirical distributions, and these results are shown in Table 2.6.

For each semester of data collection, the null hypothesis was tested that the observed total within-triad variance was equal to the mean total within-triad variance based on random assignment. The alternative hypothesis was that the observed total within-triad variance was *lower* than what was found by random assignment (a one-tailed test). The p-values associated with this hypothesis test are provided in Table 2.6. The probabilities of obtaining the observed within-triad variances all fall above an alpha level of 0.008 (reduced from 0.05 to account for six separate tests), indicating that they are not significantly lower than what would be expected by chance. These results provide evidence that the triad structure did not significantly impact the distribution of SOE-S gain scores.

Table 2.6: Results of Resampling Analysis

Semester	**Observed total within-triad variance**	**Mean total within-triad variance based on random assignment**	**Probability of randomly obtaining within-triad variance *lower* than that observed**
1	286.3	267.9	0.639
2	238.3	211.7	0.850
3	289.0	226.0	0.960
4	599.0	584.9	0.532
5	453.3	352.8	0.996
6	189.3	199.9	0.349

ANOVA Analysis of Data

Based on the analysis above, participants in the study could be considered practically independent, and an ANOVA model was used to analyze the SOE-S scores. Table 2.7 gives mean SOE-S scores and standard deviations for each treatment group at the time of pretest and posttest. A mixed between-within subjects analysis of variance was performed to compare these means. The homogeneity of intercorrelations assumption was met for these data using an alpha level of 0.001 (Pallant, 2013) (Box's Test M = 6.667, p = 0.369). The homogeneity of variance assumption was also met (Levene's Test for pretest $F_{(2,133)} = 1.388$, $p = 0.253$; for posttest $F_{(2,133)} = 0.133$, $p = 0.875$).

No significant interaction was found between participant group and pretest/posttest ($F_{(2,133)} = 0.853$, $p = 0.429$, partial $\eta^2 = 0.013$). A statistically significant main effect was found for pretest/posttest ($F_{(1,133)} = 48.116$, $p < 0.001$, partial $\eta^2 = 0.266$), with an increase in scores from pretest to posttest; the size of this effect was large (Cohen, 1988). Surprisingly, no statistically significant main effect was found for participant group ($F_{(2,133)} = 1.036$, $p = 0.358$, partial $\eta^2 = 0.015$). While engineers' SOE-S scores were apparently higher than those of the teachers, the evidence does not support a real difference in scores. This is potentially due to the small size of the sample of engineers, and thus a relatively low power to detect inter-group differences.

Table 2.7: Mean (with standard deviation) pretest and posttest scores on SOE-S

Participant Group	Pretest (of 35)	Posttest (of 35)
Student Teacher (n = 59)	23.56 (6.04)	27.90 (5.77)
Cooperating Teacher (n = 49)	24.78 (6.94)	28.12 (5.61)
Engineer (n = 28)	26.07 (5.30)	28.82 (5.48)

The results of the ANOVA analysis show a significant impact of the project on teachers' SOE knowledge. The posttest scores for all groups show room for improvement, but the gains they made over a semester provide evidence of the project's efficacy on this knowledge domain. Because the SOE-S is based on misconception items, the gains in scores reflect a reduction in inaccurate views of the SOE. That is, on the post-test participants were *more* likely to categorize non-engineering activities (e.g., building houses) as *unimportant* for engineers.

Conclusions and Implications

The present study sought to develop a way to measure the SOE knowledge of participants in a professional development project, and to assess the extent to which their knowledge changed over the course of the project. The SOE-S developed for the study showed many promising characteristics as a measure of SOE knowledge. Using the SOE-S, participants were found to have improved their SOE knowledge over the course of the project. This finding held for all participant groups (student teachers, cooperating teachers, engineers), with no differences found between the groups at pretest or posttest. Potential mechanisms by which participants improved their SOE understanding during the project include: the parts of the workshop that addressed the NOE, the presence of the engineer in the triads, and the act of planning, teaching, and communicating engineering to students (Arzi & White, 2008; Nixon, Hill, & Luft, 2017; Van Driel, Berry, & Meirink, 2014).

Although the present study cannot determine which element of the professional development project contributed most to participants' SOE knowledge growth, they do raise questions about the assumption that the engineers communicated their NOE expertise to the teachers. The SOE knowledge of the engineers was not significantly higher than that of the teachers, and all groups experienced similar gains on the SOE-S. This result is surprising, and potentially problematic for the validity of the SOE-S, given that the engineers were expected to have more expert knowledge and thus score higher on the SOE measure (Mehrens & Lehmann, 1991). Alternatively, engineering graduate students might not necessarily be NOE experts, even if they do have expertise in the content and practices of engineering. For instance, research has shown that while scientists tend to hold more accurate NOS views than the public, they do hold some degree of inaccuracy (Glasson & Bentley, 2000; Schwartz & Lederman, 2008; Yore, Hand, & Florence, 2004). The same might be the case for engineers, and even more so for the engineering graduate students in the present study, who did not necessarily have extensive experience working in the field. A further possibility is that engineers might be more knowledgeable about certain NOE domains than others. Because the present study focused only on the SOE, more work is needed to investigate engineers' views on different NOE dimensions.

Improving teachers' knowledge of the SOE, and of other NOE domains, is important if those teachers are to accurately convey the NOE to students. Yet while being knowledgeable about the NOE is necessary for accurately conveying it to students, it is not sufficient. NOS research has consistently shown that even teachers who understand the NOS do not necessarily teach it well to their students (Hacieminoglu, 2014; Lederman & Lederman, 2014; Southerland, Gess-Newsome, & Johnston, 2003). A similar situation is likely to be the case for the NOE, and additional research is needed to determine how teachers' knowledge of the SOE and other NOE dimensions intersects with their practices and with student learning.

Future Use of the SOE-S

The SOE-S developed for use in the present study shows many promising characteristics as a useful way to assess the SOE construct. Given the ongoing interest in misconceptions about the SOE (e.g., Capobianco et al., 2011; Lachapelle & Cunningham, 2014; Lambert et al., 2007), the SOE-S is likely to be of value in future studies, especially those investigating the knowledge of teachers. Importantly, the SOE-S should not be regarded as a separate survey that can be administered in isolation. The 7 SOE-S items were administered as part of a larger survey, and separating the SOE-S items would likely threaten their validity. In its current form, the SOE-S should be regarded as a method of scoring the WE survey to assess the specific SOE dimension.

The SOE-S used in this study has value, but more work is needed to further develop a SOE instrument. The items comprising the SOE-S used in the present study were all *negative* items, referring to activities that are *not* associated with engineering, which is potentially limiting. The negative items were most informative because nearly all of the participants in the present study accurately rated the positive items as important for engineers, which is consistent with prior research (Cunningham, Lachapelle, & Lindgren-Streicher, 2005, 2006; 2014; Lambert et al., 2007). The positive items used in the current study were uninformative for assessing growth in SOE knowledge, but different positive items might be developed that do not show this shortcoming. Further development of a SOE instrument should explore novel items, both positive and negative.

Finally, because the SOE-S used in the present study was created using data from adults, not students, the reliability measures may not hold for student populations. Similarly, the problems detected with certain survey items might not be present when administered to young students. Future work should work to extend SOE assessments to further populations of interest.

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CHAPTER 3. WHAT DOES "LEARNING ABOUT ENGINEERING" MEAN TO TEACHERS?

Abstract

Engineering design activities are a common way for teachers to incorporate engineering into their science classrooms. These activities can potentially promote many valuable learning outcomes related to both engineering and science. For instance, they can help students better understand science ideas as they apply them in context, while also helping students develop engineering practices and knowledge about how engineering works (Brophy et al., 2008; Lachapelle & Cunningham, 2014; NAE & NRC, 2009). However, little is known regarding how teachers prioritize different learning outcomes, and these priorities influence teaching practices (Cronin-Jones, 1991; van Driel, Beijaard, & Verloop, 2001). This study presents elementary teachers' views on what their students learned during engineering instruction, most of which was in the form of design activities, over the course of a semester. The teachers were participants in a professional development project that focused on supporting the incorporation of engineering into science instruction. The results indicate that most teachers described student learning in terms of developing designs skills and practices, while very few discussed their students' learning of engineering content. Surprisingly, teachers frequently discussed the nature of engineering as a learning outcome for students, suggesting that they prioritized this outcome relatively highly.

Introduction

Engineering is becoming an ever-more prominent component of science education in the United States at all grade levels (Moore et al., 2013), particularly with the growing adoption of the *Next Generation Science Standards* (NGSS Lead States, 2013). This is true even at the elementary level, despite the minimal preparation elementary teachers receive in the subject (Banilower et al., 2013; Diefes-Dux, 2014). In elementary contexts, a typical model of engineering instruction is the engineering design challenge, in which students engage in different aspects of engineering design, such as planning, prototyping and testing, in order to solve a problem presented to them (Lachapelle & Cunningham, 2014; NAE & NRC, 2009; NRC, 2014). Many rationales have been put forth for engaging young students in these sorts of design activities, including:

-They potentially support students' learning of science content (Cunningham & Carlsen, 2014a; NAE & NRC, 2009; Kolodner et al., 2003; Schnittka & Bell, 2011) as well as engineering concepts (Brophy et al., 2008; Lachapelle et al., 2011a; 2011b)

-They potentially support students' development of general skills such as problem-solving and teamwork (Brophy et al., 2008; Lachapelle & Cunningham, 2014; Purzer et al., 2015)

-They potentially generate students' self-efficacy in engineering and interest in it as a career (Cunningham & Lachapelle, 2010; Lachapelle & Cunningham, 2014; Lee, Miller, & Januszyk, 2014)

Research makes clear the potential for engineering design activities to positively impact student learning (Cunningham & Carlsen, 2014a), and frameworks exist that outline the characteristics of effective engineering design lessons (e.g., Moore et al., 2014). Less, however, is known about how teachers translate this model of engineering instruction into practice. Prior studies indicate that teachers have difficulty connecting science concepts to engineering design challenges (Dare, Ellis, & Roehrig, 2018; Guzey, Moore, & Harwell, 2016; Walkington et al., 2014), and that they do not equally emphasize all aspects of engineering design during instruction (Capobianco & Rupp, 2014; Hynes, 2012). While these studies indicate some ways in which teachers' practices might be improved, they reveal less about the thought processes that underlie teachers' instructional decision-making. Ultimately, achieving the noble goals of engineering instruction requires that teachers understand it, value it, and implement it in a manner consistent with the vision of this reform effort.

To better understand their teaching practices, we need to understand teachers' thinking about engineering instruction. Teachers' enactments of curricular reforms, such as engineering design, are influenced by their views about teaching and learning the subject in question (Cronin-Jones, 1991; Keys & Bryan, 2001; Pajares, 1992; van Driel, Beijaard, & Verloop, 2001). One important factor is how the teacher prioritizes the learning objectives within a subject (Wallace & Kang, 2004), as these priorities influence which learning opportunities teachers seize upon. For example, inquiry science activities often create opportunities to address nature of science (NOS) concepts with students, but teachers who do not prioritize the NOS do not take advantage of such opportunities (Herman, Clough, & Olson, 2013, 2017; Lederman, 1999). Engineering design activities similarly create many opportunities for student learning, but teachers must choose which learning goals to pursue.

The goal of the present study is to better understand elementary teachers' thinking about engineering design instruction. The teachers in the present study were participants in a professional development project aimed at supporting engineering instruction in the elementary classroom. Each participating teacher was supported by an engineering graduate student who visited the classroom on a weekly basis for a semester, with the goal of incorporating engineering into science instruction. The present study examines how the teachers participating in the project described their students' learning of engineering, including: the aspects of engineering they emphasize, and the aspects they do not. The study also compares the perspectives of the teachers in the project to those of the engineers.

Theoretical Framework

To describe and characterize the ways in which teachers describe students' learning of engineering, we developed the Engineering Learning Outcomes (ELO) Framework, shown in Figure 3.1. The framework modifies and generalizes one used by Bell, Mulvey, and Maeng (2012) to describe the interacting domains of science that are part of scientific literacy. Their framework contained three domains: science as a body of knowledge, science as a set of methods and process, and science as a way of knowing (alternatively, the NOS). The present study extends their framework to the field of engineering, which can also be described in terms of a body of knowledge, methods, and the nature of the discipline (in this case, the NOE). Because the present study is interested in domains of student learning, the "affective" domain was added to the framework. This is not a domain of engineering, but it is a relevant learning outcome related to engineering, in that students might change their attitudes and efficacy toward engineering as they learn the core components of the engineering enterprise. The four domains are summarized in Table 3.1, and are described in greater detail below.

Domains of Engineering			Affective
Practices	Concepts	Nature of Engineering	Efficacy, Attitudes

Figure 3.1: Engineering Learning Outcomes (ELO) Framework

Table 3.1: Engineering Learning Outcomes Domains, with Characteristic Elements

Domain	Elements Within Domain
Engineering Practices	-Problem definition and scoping -Brainstorming and evaluating possible solutions -Prototyping and testing -Analyzing data -Problem-solving -Working under specific constraints
Engineering Concepts	-How specific technologies function -Properties of components that comprise technologies (e.g., material properties) -How elements in complex technological systems interact
Nature of Engineering	-The kinds of tasks that engineers do (and don't do) -Descriptions of the processes that engineers use to do their work -Engineering's relationship with other disciplines -The social nature of engineering
Affective	-Self-efficacy toward engineering -Attitudes toward engineering -Interest in further study of engineering

Engineering Practices

Of the ELO Framework domains, engineering practices are the most extensively described within policy and standards documents (e.g., NAE & NRC, 2009; *NGSS*). Design is typically taken to be the core aspect of the engineering profession (Brophy et al., 2008; Dym, 1999; Kroes, 2012; Lachapelle & Carlsen, 2014b), and engineering practices are often identified as those required to engage in engineering design (Cunningham & Kelly, 2017). Examples of design-related practices include establishing the scope of an engineering problem, evaluating potential solutions, building/testing prototypes, and iteratively optimizing solutions. The degree to which students possess these skills has been assessed both at the collegiate (e.g., Atman et al., 2007; Bailey, 2008; Sims-Knight, Upchurch, & Fortier, 2005) and K-12 levels (e.g., Hsu, Cardella, & Purzer, 2014). The engineering practices domain includes both procedural and conceptual elements (Custer, Daugherty, & Meyer, 2010; Eisenhart et al., 1993). Learning engineering practices can entail developing the procedural capacities to enact them, but also learning about why those procedures work, and how they fit together into a larger approach to design.

In addition to skills that are specifically associated with engineering design, more general skills such as creativity, teamwork and problem-solving are often included within engineering practices, although they are not unique to engineering (Cunningham & Kelly, 2017; Mann, 2004). The cross-disciplinary nature of these skills is also conveyed by the *NGSS*, which, in Appendix F, identifies a set of practices relevant to both engineering *and* science. While the *NGSS* distinguishes several practices as belonging specifically to science (e.g., "constructing explanations") or engineering (e.g., "designing solutions"), many apply to both fields (e.g., "analyzing and interpreting data").

Engineering Concepts

The engineering discipline includes a base of knowledge in addition to a set of characteristic practices. While engineers utilize conceptual knowledge from the fields of science and mathematics, they also use conceptual knowledge that is unique to the discipline; engineering is not merely applied science or applied mathematics (Cajas, 2001; Kroes, 2012; NAE & NRC, 2009; NRC, 2014; Sidawi, 2009; Vincenti, 1990). Concepts unique to engineering include knowledge of planform and airfoils within aeronautics, knowledge of materials for civil engineering, and more. However, detailed examinations of the engineering knowledge base are relatively sparse (see Houkes, 2009 for a review of this issue), and the engineering concepts that are appropriate for K-12 settings are even less clear (Cunningham & Kelly, 2017; Custer, Daugherty, & Meyer, 2010; Daugherty & Custer, 2012; NRC, 2014). To illustrate this murkiness, consider the disciplinary core ideas that the *NGSS* puts forth for engineering: "defining and delimiting an engineering problem," "developing possible solutions," and "optimizing the design solution." As Cunningham and Carlsen (2014b) point out, these are statements of practices, not concepts; due to their absence and replacement with practices, the *NGSS* implies that engineering concepts are nonexistent.

For the purposes of the present study, engineering concepts include knowledge of specific technologies and how they function, knowledge of materials, and knowledge of the models used to analyze technological systems. While not intended to be an exhaustive list, these are concepts that have appeared in education literature (e.g., Lachapelle & Cunningham, 2007; 2014; NAE & NRC, 2009). Lists of engineering concepts inevitably overlap to some extent with science concepts, and certain concepts seem to straddle both knowledge bases. Material properties, for example, is regarded as a science concept in some studies, but an engineering concept in others (cf. Lachapelle et al., 2011a; 2011b; Wendell & Rogers, 2013). As Houkes (2009) argues, a sharp demarcation between engineering and scientific knowledge is not likely achievable. This is not to say that engineering concepts cannot be delineated, however, and more work is needed in this area.

The Nature of Engineering

An often-stated goal is for students to more accurately understand the structure of the engineering discipline (Cunningham & Carlsen, 2014b; Moore et al., 2014; NAE & NRC, 2008), more generally known as the "nature of engineering" (NOE; Karatas, Micklos, & Bodner, 2011). The NOE construct can be regarded as the engineering analog of the nature of science (NOS), albeit one that has received markedly less scholarly attention. While a full range of NOE ideas has not been established (see Chapter 1), some dimensions include: the scope of engineering work; knowledge about the practices of engineers; how engineers leverage knowledge and create new knowledge; and the social nature of engineering work (Brophy et al., 2008; Karatas, Bodner, & Unal, 2016; Karatas, Micklos, & Bodner, 2011; Sidawi, 2009).

Importantly, NOE knowledge should not be conflated with the knowledge of how to engage in engineering practices. The conflation of these two knowledge domains in science created well-documented problems within science education (Lederman, 2007; Lederman & Lederman, 2014), and engineering education would do well to avoid repeating those issues. Confusion is most likely to occur for NOE concepts related to how practicing engineers engage in the work of design, because these NOE concepts are often descriptions of engineering practices. The crucial distinction lies in that when students learn about what real engineers do, they are learning about the NOE. When students develop knowledge such that they can engage in engineering themselves, they are learning engineering practices. A student might understand the NOE thoroughly without being personally able to effectively design; similarly, a skilled designer might understand little about the NOE.

The Affective Domain

This final learning outcome for engineering is different from the other three in that it represents dispositions instead of knowledge. Commonly discussed affective outcomes include: self-efficacy for doing engineering, interest in engineering, and attitudes toward engineering (Hammack, Ivey, Utley, & High, 2015; Johnson et al., 2013; Marra, Rodgers, & Bogue, 2009; NAE & NRC, 2008; 2009; NRC, 2014; Roehrig, Moore, Wang, & Park, 2012). Here again, care should be taken not to conflate affective outcomes with NOE learning outcomes (Lederman, 2007; Lederman & Lederman 2014). Like the NOS, the NOE is a cognitive domain, which entails conceptual knowledge of how engineering works.

Methods

Study Context

Data were collected as part of an NSF-supported professional development and teacher education project aimed at improving the preparation of elementary teachers to teach science and engineering. Part of the project involved placing a student teacher in a triad with a cooperating teacher and an engineering graduate student ("engineer" hereafter) who worked as a team to plan and implement science and engineering activities lessons over a 16-week semester in a grades 3-5 urban classroom. The engineers spent one full day per week in the classroom with their triads. Ten triads participated each semester and were located in a variety of schools within the same diverse urban school district. Cooperating teachers and student teachers participated for one semester, and the engineers participated for two consecutive semesters.

Project participants were supported with a two-day professional development workshop at the beginning of the project as well as a one-day workshop midway through the semester. These workshops were focused on providing participants models of effective science and engineering instruction as well as methods of integrating the two subjects, establishing expectations for the semester, and helping participants effectively work together as teams. During the pre-semester workshop, an inquiry-based science lesson was modeled that utilized the learning cycle approach (Lawson, Abraham, & Renner, 1989) and emphasized a logical storyline during planning to ensure lessons contained rich concept development experiences and made sense within a multi-week unit of instruction. Participants then experienced an engineering design activity, drawn from the Engineering is Elementary (EiE, Museum of Science, Boston) curriculum, that connected to the concepts from the science lesson. Participants were made aware of the guiding principles underlying the modeled instruction, and pitfalls were also shared, including "activitymania" (Moscovici & Nelson, 1998), tinkering, children's tendency to build prior to planning, and the importance of helping students understand the role of failure. Additionally, the differences between science and engineering were addressed during the workshop. This included an emphasis on science seeking to understand the natural world, versus engineering seeking technological solutions for human problems.

During the workshops, triads were given the expectation that they find ways to incorporate engineering design into their science instruction. Triads were provided great latitude by the school district for their science instruction to modify district-provided curriculum as desired; the only limitation was the requirement to address district science standards. While implementation varied, all triads conducted at least one engineering design activity with students, and most did two or more. In addition to engineering design challenges, many triads had their engineers give presentations to students about their field of work, and about the field of engineering in general.

Research Questions

Within the context described above, we wished to better understand how participants in the project viewed their students' learning of engineering. Which learning outcomes were prioritized by participants, and which were not? The research questions guiding this work were:

1) When participants in the professional development project described what students learned about engineering, which learning outcome domains did they discuss?
2) To what extent, if any, did the engineers view what students learned about engineering differently than the cooperating teachers and student teachers?

The second research question was of interest because the engineers could potentially have held unique perspectives on student learning. Even though the engineers were part of a triad, their different educational backgrounds and their knowledge of actual engineering practice could have led them to value different learning outcomes than the other members of their triad.

Data

Each project participant completed a semi-structured interview at the end of the semester. In these interviews, participants were asked a range of questions about their experiences during the semester, including: successes and challenges during science and engineering instruction, how the triad functioned as a team, and perceptions of student engagement and learning. The full interviews typically lasted from 30-60 minutes, and were audio recorded and transcribed verbatim. Data for the present study were drawn from participants' responses to the following question: "What do you think students learned about engineering during the semester?" and its related follow-up questions.

Data were gathered from the first five semesters of project implementation. Each engineer was interviewed two times, once each semester. Because the engineers worked with different triads and in different school contexts each semester, their two interviews were treated separately. The data set for this study includes 138 total interview responses: 46 from cooperating teachers, 47 from student teachers, and 45 from engineers. Interview responses were unavailable from a small subset of participants either because they did not complete an exit interview, or did not answer the question of interest.

Analysis

A qualitative content analysis approach was used to analyze the interview data (Altheide, 1987), the goal of which was to capture the frequency with which participants discussed different engineering learning objectives by "quantitizing" the data (Miles & Huberman, 1994; Tashakkori

& Teddlie, 2009). In their responses, participants often discussed activities that students completed alongside descriptions of what students learned, but those descriptions of activities were not included because did not directly address student learning outcomes. Some participants also discussed science learning outcomes when responding to this question, and those discussions were similarly removed as they were outside of the focus of this study. In a different interview question, participants were asked what students learned about science during the semester, and some discussed engineering learning outcomes when answering the question. Responses that addressed engineering were included in the data for the present study.

Analysis began inductively by identifying and coding the discrete engineering learning outcomes that each respondent discussed (Miles & Huberman, 1994). Respondents typically discussed how students learned multiple things about engineering, and thus most interviews obtained multiple codes. Early in the coding process, broader codes were developed by grouping common ideas that emerged across multiple interviews, and these codes were iteratively refined as they were applied to the full set of interviews (Merriam & Tisdell, 2015). After the codes were developed, they were then categorized according to the ELO framework (see Figure 3.1). The final set of codes is given in Table 3.2, along with descriptions and exemplars.

To assess the reliability of the coding guide, a second researcher was trained to apply the codes, and then independently coded a subset of 30 interview responses. Cohen's Kappa statistic was then calculated to assess intercoder reliability, as this statistic accounts for chance agreements between the raters (Cohen, 1960). Kappa was calculated for each of the ELO categories shown in Table 3.2; statistics were calculated by category because the categories were of greatest of interest for the present study. In addition, many of the individual codes were not commonly assigned, and the Kappa statistic can be problematic when used for uncommon codes

(Eugenio & Glass, 2004). As indicated in Table 3.2, all but one of the categories show substantial agreement (Kappa > 0.60; Landis & Koch, 1977). The one category (Affective Domain) with moderate agreement (0.4 < Kappa < 0.6) had only one related code ("Engineering Efficacy") that was assigned infrequently, suppressing its Kappa statistic (Eugenio & Glass, 2004). Byrt, Bishop, and Carlin (1993) suggest an intercoder reliability code that adjusts Kappa for codes with low prevalence, and that statistic is also reported in Table 3.2 as "2P(A)-1:" twice the observed percent agreement minus one. Note that for all categories except the Affective Domain, the two intercoder reliability statistics give similar values.

As codes were developed from the interview data, descriptions of students' learning of skills occurred in two different ways. One set of codes, including "planning" and "working under constraints," described skills that are closely related to engineering design tasks. Another set of codes described skills, such as perseverance and teamwork, that have a more general character. Both sets of codes were categorized as "engineering practices," but the differences between them were considered interesting enough to warrant further analysis. Thus, they are separated in Table 3.2, as well as in later stages of analysis.

Table 3.2: Codes Developed During Analysis, With Categorization

Code	Description	Exemplar
Design-Related Skills (Engineering Practices) **Kappa = 0.78; 2P(A)-1 = 0.80**		
Working Under Constraints	Students learned what criteria and constraints are, and gained experience designing with them in mind.	"I think the constraints is a big part of it. We put a lot more emphasis on budgeting." (C29)
Planning Designs	Students developed skills in creating design plans; students learn the importance of planning in the context of design.	"…as painful as it has been for some of them, they've realized there is importance to planning things out before you go and do it." (E05, 1st interview)
Improving Designs	Students developed skills needed to iteratively revise and improve designs.	"…throughout the week we would talk about data that we collected, and made observations - Okay, how are we going to make this better?" (S34)
Engineering Design Process	Students learned a series of steps or tasks involved in design. They learned this at a more general level than the codes above.	"Definitely the design process, going through each one of those stages." (S05)

Table 3.2 continued

Generic Skills (Engineering Practices) Kappa = 0.75; 2P(A)-1 = 0.80		
Perseverance	Students learned how to approach and work through failures and challenges.	"They struggled and they failed and I had to have some serious motivational talks with some of my students… okay, that's not working, that's okay, now you know that doesn't work" (S31)
Teamwork	Students learned to communicate with peers and work productively with others.	"How to work as a team. They came a long way. Being confident and sharing ideas." (S28)
Problem-Solving	Students developed problem-solving skills that are often widely applicable.	"Then just problem solving and creative problem solving… it's like a personal thing for me to have kids be good problem solvers." (S22)
Nature of Engineering Kappa = 0.71; 2P(A)-1 = 0.72		
Definition of Engineering	Students learned what engineering is, and what it is not.	"It's not just about building robots. It's basically designing anything… that you know solves a problem." (E14, 2nd interview)
Fields of Engineering	Students learned that there are many engineering fields, and a bit about each.	"…so [the engineer] would introduce the different types of engineers that way…" (C32)
Science / Engineering Relationship	Students understand how science and engineering influence each other, but are also different.	"We did a couple of things where we talked about differences between science and engineering..." (S06)
Nature of Engineering Work	Students learned about how engineers do their work; not just definitional, but descriptive.	"So they know for a fact that an engineer uses their science and math skills to solve a problem…" (S20)
Engineering Concepts Kappa = 1.00; 2P(A)-1 = 1.00		
Technology	Students learned about how a technology functions, or the principles underlying a technology.	"They learned a bit about bridge aesthetics, the cost of building bridges... you may want a suspension bridge for this location or a truss bridge for this location." (C42)
Affective Domain Kappa = 0.51; 2P(A)-1 = 0.80		
Engineering Efficacy	Students developed more positive attitudes toward engineering, and grew to believe that they could do engineering.	"I think one of the biggest things is that they started to grasp the concept that they are scientists, they are engineers..." (S10)

When creating the code book, an ambiguity arose when participants discussed how their students "learned the engineering design process," which they did frequently. This statement could mean that students learned conceptual knowledge: a set of steps in a formalized "engineering design process" (EDP). However, the statement could also mean that students learned procedural knowledge: how to engage in a set of practices globally described as the engineering design process. In many cases, respondents added details that clarified their meaning, often indicating that students learned a set of EDP steps. In others, however, their meaning remained vague. Whether EDP knowledge was described by participants as procedural or conceptual, the knowledge was tied most closely to engineering practices. However, if viewed conceptually, the EDP also has ties to the NOE. Consider the similar case of a formalized, step-by-step “scientific method” in science education contexts. Students who learn such a “scientific method” can learn it as a scientific practice, using it in the context of laboratory investigations, but they are also likely to associate it with the work of real scientists, making it a NOS issue. Even though the notion of a step-by-step, universal scientific method is a NOS misconception (McComas, 1998; Woodcock, 2014), learning about it nevertheless qualifies as NOS instruction, albeit inaccurate. Learning the EDP is similarly related to learning the NOE.

Acknowledging these complexities, the “Engineering Design Process” code was categorized under “engineering practices” for the present study. This categorization was made to best capture respondents’ meaning. Although NOE connections to the EDP exist, when respondents elaborated on the EDP, they discussed it in relation to students’ doing of engineering rather than the EDP in the context of the work of practicing engineers. Those who did not elaborate on the EDP are assumed to have thought about it similarly, although we acknowledge that this may not have been true for all cases. Although we made this coding choice, the NOE implications of the EDP learning outcome should not be ignored, and are examined in more detail in the discussion section.

Results

Table 3.3 provides the proportion (with standard error) of interviews that were assigned each of the codes listed in Table 3.2, disaggregated by participant group. Each cell in the table indicates the proportion of interviews from a given participant group that were assigned a given code. In addition, the table provides the proportion of interviews that were given at least one code in each of the major code categories, shown in bold font. Because interview responses were typically assigned more than one code, the columns in Table 3.3 sum to more than 1.00. The two most frequently assigned codes were for students' learning the EDP and their learning of what engineering is, and this was the case for all participant groups. Other common codes were the practices of planning and improving designs, and the NOE ideas of the different fields of engineering and the science/engineering relationship. Participants rarely discussed student learning in the engineering concepts or affective domains, each of which only had one related code.

Table 3.3: Proportion of interview responses with each code (with standard errors)

Code	Coop Teachers (n=46)	Student Teachers (n=47)	Engineers (n=44)
Design-Related Skills (Engineering Practices)	**0.70 (0.06)**	**0.72 (0.07)**	**0.76 (0.07)**
Working Under Constraints	0.13 (0.05)	0.11 (0.04)	0.13 (0.05)
Planning	0.24 (0.06)	0.15 (0.05)	0.27 (0.07)
Improving Designs	0.24 (0.06)	0.06 (0.04)	0.29 (0.07)
Engineering Design Process	0.46 (0.07)	0.68 (0.07)	0.47 (0.07)
Generic Skills (Engineering Practices)	**0.35 (0.07)**	**0.28 (0.07)**	**0.40 (0.07)**
Perseverance	0.20 (0.06)	0.09 (0.04)	0.22 (0.06)
Teamwork	0.17 (0.06)	0.13 (0.05)	0.24 (0.06)
Problem-Solving	0.04 (0.03)	0.13 (0.05)	0.04 (0.03)
Nature of Engineering	**0.59 (0.07)**	**0.81 (0.06)**	**0.69 (0.07)**
Definition of Engineering	0.46 (0.07)	0.43 (0.07)	0.40 (0.07)
Fields of Engineering	0.17 (0.06)	0.26 (0.06)	0.22 (0.06)
Science / Engineering Relationship	0.17 (0.06)	0.32 (0.07)	0.20 (0.06)
Nature of Engineering Work	0.24 (0.06)	0.17 (0.05)	0.17 (0.06)
Engineering Concepts	**0.11 (0.05)**	**0.00 (0.00)**	**0.09 (0.04)**
Technology	0.11 (0.05)	0.00 (0.00)	0.09 (0.04)
Affective Domain	**0.11 (0.05)**	**0.11 (0.04)**	**0.18 (0.06)**
Engineering Efficacy	0.11 (0.05)	0.11 (0.04)	0.18 (0.06)

Table 3.4 provides the proportion of interview responses from each participant group that were categorized under each of the four ELO domains, with the "Engineering Practices" domain separated into components of "Deign-Related" and "Generic" skills. To determine whether the proportion of interviews addressing each learning outcome category were the same for each participant group, a Chi-Squared Test of Homogeneity was performed. This test was not

performed on the "Engineering Concepts" category, due to the low incidence of interviews with that categorization. Because five comparisons were made, tests were performed at α = 0.01.

Table 3.4: Proportion of Interview Responses Addressing Each Domain

Category	Cooperating Teachers (n=46)	Student Teachers (n=47)	Engineers (n=45)	Homogeneity Test
Engineering Concepts	0.11	0.00	0.09	N/A
Engineering Practices	0.80	0.81	0.82	$X^2 = 0.01$, df = 2, p = 0.97
Design-Related	0.70	0.72	0.76	$X^2 = 0.11$, df = 2, p = 0.94
Generic	0.35	0.28	0.40	$X^2 = 1.04$, df = 2, p = 0.42
Nature of Engineering	0.59	0.81	0.69	$X^2 = 1.64$, df = 2, p = 0.11
Affective	0.11	0.11	0.18	$X^2 = 1.15$, df = 2, p = 0.52

Table 3.4 illustrates several important patterns in participants' responses. First, across all participant groups, both Engineering Practices and Nature of Engineering learning outcomes were commonly mentioned. For the case of engineering practices, participants most commonly discussed design-related skills; very few participants discussed more generic skills without also discussing design-related ones. Engineering concepts were rarely discussed by participants, as were outcomes in the affective domain. As can be seen from the results of the homogeneity tests, the pattern of responses between participant groups was equivalent for each learning outcome category.

The similarity of responses across the three participant groups is potentially due to the triad structure, which is a source of non-independence of participants. Triad members could have given similar responses, which would result in lower X^2 test statistics. To investigate this possibility, a bootstrap resampling method was used (Efron, 2003). The full data set was resampled using two parallel methods. In the first method, the data were resampled such that only one participant from each triad was present in the subsample. In the second method, the data were resampled randomly, but with the condition that the number of participants in each group (cooperating teachers, student teachers, engineers) was the same as that sampled during the first method. For each subsample, X^2 test statistics were calculated for each ELO category except "Engineering Concepts." The resampling procedure was iterated 10^5 times to develop an empirical distribution of X^2 test statistics for each of the two resampling methods, and these distributions were then compared.

If the triad structure caused the similarity in participant groups' responses, then the second resampling method (which admitted participants from the same triad) should result in *lower* X^2 test statistics than the first method (which prohibited participants from the same triad). Table 3.5 presents the results of the resampling analysis. For each of the ELO categories, Table 3.5 gives the mean (with standard deviation) X^2 test statistic obtained by each of the resampling methods. The distributions of X^2 test statistics obtained by each resampling method were nearly identical; the methods return different statistics only for the "Generic" practices category, and the difference between the methods was minimal. The results of the resampling analysis indicate that the similarity between participant groups *cannot* be attributed to the triad structure.

Table 3.5: Resampling Analysis Results

ELO Category	Mean X^2 (and SD) for Method 1	Mean X^2 (and SD) for Method 2
Engineering Concepts	N/A	N/A
Engineering Practices	0.27 (0.27)	0.25 (0.25)
Design-Related	0.41 (0.41)	0.41 (0.40)
Generic	1.03 (0.99)	1.25 (1.18)
Nature of Engineering	1.00 (0.80)	0.99 (0.80)
Affective	1.60 (1.50)	1.59 (1.49)

Discussion

The results from the present study indicate that project participants described students' learning primarily in terms of engineering practices and the NOE, and that this pattern was observed for all participant groups (student teachers, cooperating teachers, and engineers). The focus on engineering practices is not surprising. As discussed above, the *NGSS* describes engineering almost exclusively in terms of practices (Cunningham & Carlsen, 2014b), and engaging students in the activity of engineering design is typically at the forefront of elementary education efforts (Brophy et al., 2008; Lachapelle & Cunningham, 2014), including curriculum materials used by several triads. On the other hand, the high proportion of participants who discussed students' learning of the NOE is an unexpected finding, especially given the well-documented difficulties in getting teachers to address the NOS with students (Herman, Clough, & Olson, 2013; Lederman & Lederman, 2014). While the most commonly addressed NOE idea was a general and perhaps superficial description of engineering work, a substantial proportion of participants discussed students' learning of more in-depth NOE issues, such as the relationship between engineering and science.

Several interpretations of the NOE result are possible. One is that the portions of the workshops that addressed the NOE substantially impacted participants, even though they were brief in duration. This would imply a receptiveness among teachers to addressing the NOE which does not seem to exist for the NOS (Herman, Clough, & Olson, 2013; Lederman & Lederman, 2014). Another explanation is that project participants were primed to consider NOE learning outcomes because of the presence of an engineer in the classroom, which naturally raises the issue of "What is an engineer?" and "What does an Engineer do?" The engineers were often regarded as ambassadors of their fields, and when they introduced themselves to the students, they often described their field of work and the field of engineering more broadly. This interpretation implies that the elementary teachers would not have been attuned to the NOE without the presence of the engineers, and perhaps would not emphasize the NOE in the future when the engineer is no longer present.

A third possibility is that the relative attention to NOE learning outcomes is related to the vagueness of the engineering concepts domain. When teaching engineering, teachers are not pressured to address engineering content, which frees them to consider the NOE as a relevant objective to pursue. A very different case exists for science instruction, where pressure to cover the science content can suppress the teaching of NOS, even for those teachers who understand it and value it (Abd-El-Khalick, Bell, & Lederman, 1998; Lederman, 1999; Lederman & Lederman, 2014). Finally, some combination of the three explanations may account for these findings. For instance, the introduction of the engineer to the triad and the students as an "engineer" provided opportunities to address "what is engineering" and "what do engineers do." When professional development workshops emphasized the importance of students understanding the distinctions between science and engineering so that science is not devalued, teachers may have seen the importance of helping children learn the NOE. Additionally, teachers' efforts were not impeded by pressure to cover engineering concepts—opening "space" to address not only engineering practices, but lessons about the NOE.

The present study is not able to tease apart these explanations, but it does make clear the need to further investigate how teachers think about the NOE, as well as how they address it with students. To what extent would teachers value NOE learning outcomes if they were not part of a professional development project such as the one in the present study? More importantly, to what extent do teachers' instructional practices reflect their NOE learning goals? While teachers' objectives for student learning are important, they do not determine what occurs in the classroom. Teachers who intend to address certain ideas with students do not always implement practices consistent with their intentions (Abd-El-Khalick, Bell, & Lederman, 1998; Estapa & Tank, 2017). This concern was somewhat mitigated by asking teachers after instruction what they felt students learned about engineering, which is different than seeking in advance what teachers hope their students will learn from upcoming instruction (Estapa & Tank, 2017). In this case, teachers were free to discuss *ex post facto* what worked well as well as the struggles they and their students encountered. Finally, given the limited preparation that elementary teachers have in engineering, to what extent do their teaching practices *accurately* convey the NOE?

An issue related to this last question is that of the engineering design process (EDP). The results from this study indicate that about half of participants discussed students' learning of the EDP, either broadly or as a series of formalized steps. This result is likely due in part to the professional development workshops they experienced, in which participants took part in an *Engineering is Elementary* lesson employing a simple 5-step EDP model. Additional materials from that curriculum were available to participants upon request, and many utilized them. As a result, the *Engineering is Elementary* EDP model was a common feature in classrooms. While this learning outcome was classified under "engineering practices," it has important implications for students' NOE learning, because students are likely to associate EDP models used in the classroom with the work of practicing engineers.

The existence of a generalized EDP that transcends the various subfields of engineering is a matter of some controversy (Kroes, 2002; Mitcham, 1994). Cross (2000), for example, suggests that a very general iterative model of "analysis – synthesis – evaluation" (p. 38) describes the various engineering fields reasonably well, but also warns that many EDP models do not describe actual practice. Kroes (2002) argues that more complex EDP models are domain-specific, depending on the technology in question. Further, Kroes argues that EDP models are not so much *descriptive* of engineering practice as they are *prescriptive*: they indicate how design activities ought to be organized. Typical EDP models used in classrooms are resolved into cycles of prescriptive steps, such as the five-step model of *Engineering is Elementary*, the seven-step model of *Teach Engineering* (www.teachengineering.org/k12engineering/designprocess), and others (e.g., Bailey & Szabo, 2007; Hirsch et al., 2013; Wendell & Rogers, 2013). As prescriptive EDP models, they reflect the work of design methodologists who aim at improving design processes (Kroes, 2002). However, these relatively simple EDP models have been criticized as misrepresenting the work of actual designers (e.g., Bucciarelli, 1988; Crismond & Adams, 2012; Mawson, 2003; Williams, 2000). Because K-12 teachers tend to describe EDP models only superficially to their students (Hynes, 2012), students are not likely to be aware that these EDP models are more *prescriptive* than *descriptive*, which is highly problematic in terms of conveying an accurate sense of the NOE. More empirical work is needed in this area to fully investigate these implications.

Implications

Although policy documents and curricula emphasize the importance of engineering practices, they give little attention to the NOE. Nevertheless, teachers have an interest in the NOE as a learning goal, and given concerns about the potential conflation of science and engineering (e.g., McComas & Nouri, 2016; Zeidler et al., 2015), teachers ought to be supported in this domain. Standards documents such as the *NGSS* provide little guidance to teachers on what NOE ideas to address, or how to address them. Moreover, the ubiquitous presence of formalized and linear EDP representations in engineering curriculum materials creates the potential for inaccurate NOE portrayals. Further research is needed to more fully investigate the ways in which teachers address the NOE during engineering instruction, and how to support them in their NOE teaching practices.

Another area that requires more attention in the engineering education literature is that of engineering concepts. Teachers rarely mentioned students' learning of engineering concepts, which is not surprising given the lack of clarity in this domain (Custer, Daugherty, & Meyer, 2010; Daugherty & Custer, 2012; NRC, 2014). Even though engineering concepts are given little attention, they are nevertheless important. How are students to engage in engineering design if they do not have access to the relevant conceptual knowledge base? Math and science knowledge are not sufficient for engaging with genuine engineering problems (Kroes, 2012), thus, engineering concepts that are appropriate for elementary students need to be articulated. When vagueness surrounds this knowledge domain, the results of the present study indicate that teachers are likely to ignore it as a relevant learning outcome.

In summary, this study provides insight into how elementary teachers think about the objectives of engineering instruction after having a 16-week experience that included teaching engineering concepts to their students. Their perspectives about engineering instruction are not necessarily the same as those for science instruction, and this is important for both teacher educators and education researchers to consider. Given elementary teachers' emphasis on promoting engineering practices and the NOE, how can teacher educators best prepare them to address these domains? To what extent is the relative lack of attention to other learning outcome domains (engineering concepts and affective outcomes) problematic, and how might elementary teachers be made more aware of these? As engineering instruction becomes increasingly common in elementary classrooms as part of science instruction, these are vital questions for the science education and engineering education fields to consider.

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CHAPTER 4. ELEMENTARY TEACHERS' PORTRAYALS OF THE NATURE OF ENGINEERING

Abstract

Engineering is increasingly becoming part of science education efforts in United States classrooms, often taking the form of engineering design activities (Crismond & Adams, 2012; Moore et al., 2013; NGSS Lead States, 2013). One goal of engaging students in engineering instruction is for students to better understand the *nature of engineering* (NOE): what engineering is, what engineers do, and how engineering is related to other fields of study such as science (NAE & NRC, 2008; NRC, 2012). However, very little is known about how teachers communicate the NOE to students in the context of engineering instruction. The present study reports a multiple case study of engineering instruction in four elementary (grades 3-5) classrooms, and the way in which the NOE was conveyed during instruction. In each classroom, an elementary student teacher and cooperating teacher were teamed with an engineering graduate student and tasked with incorporating engineering into science instruction over the course of a semester. During the semester, each group of participants explicitly addressed the NOE with students, but with the exception of one group, explicit NOE was infrequent. On the other hand, the engineering activities that were implemented by the participant groups conveyed many implicit NOE messages to students. While some of these messages were reasonable, others distorted the NOE, and many messages were communicated that the participants did not intend to send.

Introduction

At all grade levels, growing efforts are occurring within the United States to incorporate engineering into K-12 education, particularly into science instruction (Moore et al., 2013; NGSS Lead States, 2013, Crismond & Adams, 2012). At the elementary level, the integration of engineering typically takes involves engaging students in engineering design activities (Dym et al., 2005). Design activities can take many forms, but typically include presenting students with an engineering problem to address, then guiding students through the practices involved with solving that problem such as: planning and designing potential solutions to the problem, creating and testing prototypes, and revising their designs (Lachapelle & Cunningham, 2014; NAE & NRC, 2009; NRC, 2014). Design activities can be used to support the learning of science content (Crismond & Adams, 2012; Cunningham & Carlsen, 2014a), but goals specific to engineering also exist, such as developing students' design skills (Brophy et al., 2008; Mentzer, Becker, & Sutton, 2015; NAE & NRC, 2009; NGSS Lead States, 2013). In addition, a commonly stated objective for engineering instruction is that students come to better understand the nature of engineering (NOE): what engineering is, what engineers do, and its relationship to other disciplines (Karatas, Micklos, & Bodner, 2011; Moore et al., 2014; NAE & NRC, 2008; NRC, 2012).

Even though accurately communicating the NOE to students is a commonly stated goal for engineering instruction, very little research has investigated the NOE teaching practices of teachers. Some studies have examined teachers' NOE knowledge, and have documented misconceptions that teachers and students hold about what engineering is and what engineers do (Capobianco et al., 2011; Cunningham, Lachapelle, & Lindgren-Streicher, 2006; Lachapelle & Cunningham, 2007; 2014; Lambert et al., 2007) as well as how engineering is related to science (Antink-Meyer & Meyer, 2016; Karatas, Micklos, & Bodner, 2011). For teachers, evidence shows that professional development experiences can improve teachers' NOE views (Duncan, Diefes-Dux, & Gentry, 2011; High et al., 2009), although the NOE is rarely the focus of these professional development efforts. An exception to this is a recent study by Hasan, Yesilyurt, Kaya, and Trabiya (2017), in which the teachers experienced explicit NOE instruction during an authentic design experience. The studies cited above, however, focus on the NOE *knowledge* of teachers in professional development contexts, as opposed to the NOE *instruction* that those teachers implement with students.

The present study begins to explore teachers' NOE teaching practices by investigating how elementary teachers communicated the NOE to their students while implementing engineering design activities in their classrooms. The present work was conducted in the context of an NSF-funded professional development project that supported elementary teachers' science and engineering instruction.

Theoretical Framework

The present study is informed by the situated perspective of learning advanced by Lave and Wenger (1991). Lave and Wenger challenge the notion that learning is an individual process of obtaining abstract knowledge that can then be applied in the "real" world. Instead, they describe learning as a process by which newcomers enter *communities of practice* by engaging in *legitimate peripheral participation*, a process that is typified by the traditional apprenticeship. As learners engage in disciplinary activities, they move toward full participation in the disciplinary community. In this perspective, what an individual learns is inseparable from the contexts and activities in which the learning occurs.

Lave (1997) points out that communities of practice are no less present in formal schooling than they are in professional contexts. School classrooms contain characteristic tasks, activities, assignments, and examinations that students navigate as they would any other cultural situation. Lave argues, however, that the practices that students develop in school contexts may not be those that the teacher intends students to learn. In a science classroom, for instance, the teacher may intend students to acquire the skills and practices of the science discipline; in reality, students might instead learn to "improvise on the production of that practice but not the practice itself" (p. 33). Students in classrooms engage in legitimate peripheral participation no matter the context, but the crucial question is the extent to which the classroom community of practice is related to the community of practice targeted by instruction.

Brown, Collins, and Duguid (1989) similarly voice concern over the *authenticity* of educational activities. They caution that when disciplines are transformed as they are brought into formal classroom environments, students end up engaging in "ersatz activity" (p. 34) rather than the genuine activities of the target discipline. This concern has implications for how students learn about the nature of a discipline. When students engage in legitimate peripheral participation, they learn not only how to engage in certain practices, but also gain a sense of how the community of practice is structured. Yet if students engage in only ersatz activities, they "are likely to misconceive entirely what practitioners actually do" (Brown, Collins, & Duguid, 1989, p. 34).

From the situated perspective, if a goal of engineering education is to accurately convey the NOE, then a crucial factor is how classroom engineering activity relates to the engineering discipline. To what extent do classroom activities engage students in *authentic* practice? The degree of authenticity influences the extent to which students come to accurate understandings of the NOE. Those who engage only in "ersatz" activities may misconstrue what real engineering is like (Brown, Collins, & Duguid, 1989). In contrast, students who engage in more authentic engineering tasks in the classroom are likely to develop more accurate NOE views.

NOE Framework

The NOE framework used to guide the present study is summarized in Table 4.1. This framework is informed by the work of Matthews (2012) regarding how to define the NOS construct. Matthews argues that the best way to describe the NOS is by identifying "features of science (FOS) to be elaborated, discussed and inquired about" (p. 15). Following this suggestion, Table 4.1 describes the NOE in terms of a set of disciplinary features. Associated with each feature are a set of questions that identify essential lines of inquiry related to the NOE. The NOE features and associated questions were identified by the author by synthesizing philosophical, historical, and sociological studies of the engineering discipline (see Chapter 1 for a more detailed discussion). While not comprehensive, the nine features identified during this review comprise the major NOE dimensions that were of interest to scholars of the engineering discipline. These nine features also guided the present study's inquiries into teachers' NOE instruction.

Table 4.1: NOE Framework

Feature of Engineering	Relevant Questions
1. Design in Engineering	-What does it mean for an engineer to design a technology? -What are the inputs and outputs of engineering design? -How is engineering design different from design in other disciplines?
2. Specifications, Constraints, and Goals	-How are the specifications and constraints of an engineering project determined? -How flexible are the goals and constraints of a given project?
3. Sources of Engineering Knowledge	-How do engineers use knowledge from other disciplines, such as science? -What kinds of knowledge are internal to the engineering discipline?
4. Knowledge Production in Engineering	-How do engineers produce the knowledge needed to engage in design? -What kinds of activities constitute "engineering science?"
5. The Scope of Engineering	-What roles do engineers play within technological projects? -What kinds of technological activities do engineers **not** generally do?

Table 4.1 continued

6. Models of Design Processes	-What models exist of the engineering design process? -How do models of the design process relate to the real work of designers?
7. Cultural Embeddedness of Engineering	-In what ways are engineers influenced by the culture in which it is practiced? -In what ways must engineers think about society during design?
8. The Internal Culture of Engineering	-What characteristics, if any, are common to engineers? -To what extent does an "engineering culture" exist?
9. Engineering and Science	-How do engineering and science influence one another? -In what respects are engineering and science different?

Literature Review

The goal of accurately conveying the NOE to students is comparable with the perennial science education goal of promoting students' understanding of the nature of science (NOS). Because the NOE is a relatively unexplored domain, the present study thus draws heavily from the NOS research base. An important distinction made within NOS research, one that is highly relevant for the present study, is that between *implicit* and *explicit* NOS instruction (Abd-El-Khalick & Lederman, 2000). The situated perspective on learning, outlined above, presents the implicit way students learn about a discipline such as science. It is implicit in the sense that students' attention may never be overtly drawn to the nature of the discipline in question, but they nevertheless develop ideas about how the discipline is structured. The implicit process occurs whether or not teachers intend to convey the structure of a discipline. As Clough (2006) points out, "despite teachers' intentions, science courses cannot escape conveying an image of the NOS to students" (p. 464). In contrast, explicit NOS instruction occurs when students' attention is overtly drawn to the science discipline, and students' NOS ideas are elicited and discussed.

In science classrooms, implicit NOS instruction occurs in a variety of ways, including the language teachers use to communicate science ideas, the way that scientific knowledge is represented in textbooks, and the types of laboratory activities students experience. However, the implicit NOS messages that students receive from these channels is often inaccurate and thus creates and/or reinforces pervasive NOS misconceptions (Clough, 2006; Lederman, 1986; McComas, 2003; Olivera, Akerson, Colak, Pongsanon, & Genel, 2012; Zeidler & Lederman, 1989). To promote more accurate NOS views, many have argued for engaging students in more “authentic” scientific inquiry experiences (Crawford, 2014; NRC, 2012; Roth, 1995; Roth & McGinn, 1998). For example, Bybee and Van Scotter (2007) argue, “As they model how scientists do their work, students develop a better understanding of the process of scientific inquiry” (p. 46).

Yet even under the best of conditions, differences will exist between the activities of students in science classrooms and those of practicing scientists (Abd-El-Khalick et al., 2004). Explicit instruction can help students recognize those differences and come to an accurate understanding of the NOS despite them. In addition, explicit instruction is crucial to dislodge problematic NOS ideas that students developed from prior educational experiences (Bell, Mulvey, & Maeng, 2016; Clough, 2006). Students often have strong NOS misconceptions, developed over years of experiences in and out of school (Lederman, 2007; Lederman & Lederman, 2014; McComas, Clough, & Almazroa, 2000). Students interpret instructional experiences through the lens of their misconceptions, and distort classroom experiences to fit the misconceptions they hold (Tao, 2003). Thus, not surprising is the finding that explicit instruction is needed for students to replace their misconceptions with accurate NOS understanding (Abd-El-Khalick & Lederman, 2000; Clough, 2006; Khishfe & Abd-El-Khalick, 2002; Lederman & Lederman, 2014).

The strengths and limitations of implicit NOS instruction are illustrated by studies that have examined students' NOS learning in the context of student-scientist partnerships in which students take on an *apprentice* role. Advocates for such apprenticeships often argue that, on account of their authenticity, they will promote students' understanding of the NOS (e.g., Barab & Hay, 2001; Ryder, Leach, & Driver, 1999). In their review of research of science apprenticeship programs, Sadler, Burgin, Mckinney, and Ponjuan (2010) found evidence that certain NOS ideas can be implicitly communicated in these contexts, including: the complexities of scientific research, the social aspects of doing science, and the challenges involved in obtaining accurate and reliable data. However, students did not show gains with respect to more nuanced epistemological NOS issues, such as the tentative character of science ideas or the ways in which social factors influence scientific thought. Students' ideas about certain NOS concepts only improved in cases where they were *explicitly* addressed during the apprenticeship experiences (Bell, Blair, Crawford, & Lederman, 2003; Schwartz, Lederman, & Crawford, 2004).

Applications to the Nature of Engineering

How can research on explicitly and implicitly teaching the NOS be translated to the situation of NOE instruction? Engineering and science are closely related fields and are frequently expected to be taught side-by-side in the context of science instruction, but several important differences exist in how they are treated in K-12 education. First, engineering is a relatively novel discipline in K-12 schooling, particularly at the elementary level (Diefes-Dux, 2014; Lachapelle & Cunningham, 2014); only 1% of elementary teachers report having taken engineering coursework, though almost all have had coursework in science (Banilower et al., 2013). While NOE misconceptions have been documented in elementary students (Capobianco et al., 2011; Lachapelle & Cunningham, 2007; 2014), students at all grade levels have likely received little, if any, formal instruction in engineering, let alone NOE instruction. Whatever misconceptions students hold about the NOE are likely developed in out-of-school contexts, and they may not be held as tightly as those about the NOS.

The characteristics of typical science and engineering instruction also differ. Although standards documents such as the *NGSS* (Lead States, 2013) and *NSES* (NRC, 1996) place value on scientific practices, science instruction typically emphasizes students' learning of science concepts. In contrast, engineering instruction tends to give little attention to specific concepts, focusing instead on activities and processes (Daugherty & Custer, 2012). This is evident in the design challenge model of engineering instruction (Brophy et al., 2008; Dym et al., 2005; NAE & NRC, 2009), as well as the *NGSS*'s focus on engineering practices rather than engineering concepts (Cunningham & Carlsen, 2014b). In these respects, engineering education has had an enduring focus on providing students with experiences that are intended to be as "authentic" as possible (Crismond & Adams, 2012; Guzey et al., 2014; Mentzer, Becker, & Sutton, 2015; Moore et al., 2014; NAE & NRC, 2009).

Despite the differences between K-12 science and engineering education, teaching and learning about the NOE is likely to have much in common with the NOS. Whether they intend to or not, teachers inevitably communicate the NOE to their students during engineering instruction, just as is the case for the NOS during science instruction (Clough, 2006). If engineering instruction predominantly takes the form of design activities, then these will be the primary mode of implicit NOE instruction. The NOE can also be addressed explicitly, and explicit NOE elements are included in curricular materials such as *Engineering is Elementary* (Museum of Science, Boston) and LEGO Engineering (Wendell et al., 2014). In the absence of explicit NOE instruction, then of central importance are the implicit messages communicated to students during design activities. Additionally, a key concern is the degree to which the NOE is accurately communicated, whether explicitly or implicitly (Diefes-Dux, 2014).

Methods

Context of the Study

The present study was conducted as part of an NSF-funded STEM-C project that aimed to improve the preparation of elementary teachers to teach science and engineering. Student teachers were placed with a cooperating teacher and an engineering graduate student ("engineer" hereafter) in a grade 3-5 urban classroom in the Midwest. Working as a team, these triads were tasked with developing innovative and engaging science lessons and finding ways to integrate engineering into science instruction. Acting as content area experts, the engineers spent one full day per week in the classroom with their triads and supported the teachers in both the planning and implementation of science and engineering lessons.

The triads were supported by a two-day professional development workshop prior to the beginning of the semester, and a one-day workshop midway through the semester, although the engineers did not participate in the second workshop. During these workshops, science activities following a Learning Cycle approach (Lawson, Abraham, & Renner, 1989) were modeled for participants, along with engineering design activities drawn from the *Engineering is Elementary* (*EiE*; Museum of Science, Boston) curriculum. The workshops emphasized how to conceptually link science and engineering lessons within an instructional unit and also provided time for the triads to begin work on their own instructional units with the guidance of project staff. The workshops also provided participants with a brief overview of NOE concepts, with emphasis placed on the relationship between science and engineering.

During the semester, the engineers were supported with an on-campus course run by project staff that met weekly. In addition, triads were regularly visited by project researchers, who also provided feedback and support for science and engineering instruction.

Research Questions

The study sought to better understand the NOE instructional practices of participants in the professional development project described above. The research questions guiding the study were:

1) What NOE ideas were explicitly and implicitly conveyed to students during engineering instruction by the triads involved in the professional development project?
2) How did the NOE ideas that were *actually* conveyed by the project participants compare with what the triads *intended* to convey?

Methodology

This study employed a multiple case study design (Yin, 2014), using the triad as the unit of analysis. Each triad operated within a unique school context, but all cases were bounded by the common context of the professional development project. The triads were treated as the unit of analysis because the engineering lessons delivered to students were products of the triads' collective efforts. Although the individual triad members played different roles and brought different knowledge and perspectives to their triads, the instructional activities were products of the triad, not any individual member.

A multiple case study design was deemed most appropriate for the present study as the phenomenon of NOE instruction cannot be separated from its complex real-world context (i.e., schools). An adequate description of NOE instruction, as well as the contextual factors affecting it, demands a detailed examination of the phenomenon using multiple sources of evidence.

Furthermore, the use of multiple cases permits more generalizations to be made about how NOE instruction occurs in contexts that differ (Yin, 2014).

Participants

Four triads participated in the present study, each composed of a cooperating teacher, student teacher, and engineer. All four triads were situated in grades 3-5 in the same urban school district, but in different school buildings. Demographics for the four participating triads are shown in Table 4.2. As seen in Table 4.2, participants brought with them a range of professional and educational experiences. While all cooperating teachers held graduate degrees, they varied in classroom experience: Cindy was relatively early in her teaching career, while the other three teachers all had more than 15 years of teaching experience. In addition, two of the cooperating teachers, Charley and Catherine, had previously participated in the professional development project. The engineers represented four different engineering specializations, showing a range of educational backgrounds, and three of the engineers were international students. Table 4.3 provides demographic information for the school contexts of each of the four triads. While these schools were in the same district, they show a wide range of demographic characteristics.

Table 4.2: Participant Demographics

Triad, Grade	Participant	Role	Background Characteristics
Triad 1 5th Grade	Charley	Cooperating Teacher	25 years teaching experience Repeat project participant Holds Master's degree
	Susan	Student Teacher	Social Studies and Science Endorsement
	Emma	Engineer	Agricultural Engineering

Table 4.2 continued

Triad 2 3rd Grade	Catherine	Cooperating Teacher	16 years teaching experience Repeat project participant Holds Master's degree
	Sheila	Student Teacher	Reading and Math Endorsement
	Emerson	Engineer	Chemical Engineering
Triad 3 4th Grade	Cindy	Cooperating Teacher	4 years teaching experience Holds Master's degree
	Sam	Student Teacher	English as Second Language and Reading Endorsement
	Ethan	Engineer	Mechanical Engineering
Triad 4 4th Grade	Carol	Cooperating Teacher	22 years teaching experience Holds Master's degree
	Sonia	Student Teacher	Unknown Endorsement Areas
	Erik	Engineer	Aerospace Engineering

Table 4.3: School Demographics and Class Size

Triad / School	Class Size	School Enrollment	School %ELL	School %White	School %Free/Reduced Lunch
Triad 1 / East	24	392	2	72	41
Triad 2 / South	28	650	29	32	83
Triad 3 / West	25	269	6	71	61
Triad 4 / North	20	280	6	58	72

Data Collection

An essential component of case study research is the use of multiple sources of evidence to develop "converging lines of inquiry" (Yin, 2014, p. 97). Data collection occurred during Fall 2017, and included the following sources:

Classroom Observations. The researcher observed lessons taught or planned by the triad throughout the semester, which included science and engineering lessons. Only observations of engineering lessons, as identified by the participants, were used for the present study. Observations focused on recording the overall sequence of instructional activities, verbal interactions between the teachers and students, and the engagement of students with the instructional tasks.

Planning Documents. Each triad gave the researcher access to the planning documents that the triad used for engineering lessons during the semester. These documents were not prepared for the benefit of the researcher, but rather were the plans that were utilized by the triad for instructional purposes.

Informal Interviews. Informal interviews were typically conducted before or after a lesson was observed and were most often conducted with two or three triad members simultaneously. While they lacked a formal structure, they were organized around the following central questions: “What are/were your goals/objectives for student learning in this lesson?” and “What progress do you think students made toward your goals/objectives?” Whenever possible, these interviews were audio recorded.

Participant Correspondence. Emails exchanged with project participants were used as a data source when they included descriptions of instruction, or participants’ reflections on instruction. Such emails were typically exchanged when the researcher was unable to observe an engineering lesson, or when an informal interview was not logistically possible. Emails were addressed to all triad members and responses were generally accessible to all parties.

Formal Semi-Structured Exit Interviews. Each participant in the project completed an approximately 45-minute interview with project staff at the end of the semester. Interview questions addressed how participants viewed student learning, how the triad functioned as a team, and what the triad members learned from the experience. Exit interviews were audio recorded and transcribed verbatim.

Positionality of the Researcher

All data sources, excepting the formal exit interviews, were collected by the author, who also played an active role in the professional development goals of the project. Research visits to classrooms were not merely observational, but were also intended to support triads' instruction. A critical issue to navigate within these two roles was how to provide support without inserting the researcher's goals into the classroom. To handle this concern, support was always offered to participants in the context of *their* instructional goals. The researcher provided feedback and guidance to participants when solicited, but the first question posed to participants was always for them to describe their goals for a given lesson, and feedback was tailored to the participants' stated goals. Only when participants specifically asked about how to more accurately convey the NOE to students did the researcher provide any NOE-specific guidance; such NOE-oriented feedback was rarely solicited.

Importantly, the project participants completing the present study were unaware that examining NOE instruction was the primary focus. Participants understood that the researcher was interested in examining how they implemented engineering instruction in their classrooms, and the NOE was addressed in the professional development workshops, but the NOE was not communicated to be a focus of study to the participants. In this regard, participants' NOE instruction can be regarded as typical of any participants in the professional development project.

Data Analysis

To address Research Question 1 and describe the explicit and implicit instruction of the participants in the study, the triads were treated as the units of analysis (Yin, 2014). Analysis focused on field notes collected from observed lessons, participants' planning documents, and informal interviews and correspondence with participants. From these data sources, case summaries were created that described each triad's engineering instruction over the course of the semester. Concise case summaries were then sent to each member of participating triads as a source of respondent validation (Miles & Huberman, 1994). Participants were asked to identify any inaccuracies in the case summaries, and to identify any additional instances of engineering instruction that were not included in the summaries. If additional engineering lessons were identified, participants were asked to describe those lessons, and provide planning documents if possible.

To describe explicit NOE instruction, the case summaries were examined for instances in which the engineering discipline was *overtly* referenced during a lesson. For example, when a triad member explains to students that engineers are often limited by cost when they engage in design, this is an instance of explicit NOE instruction. In contrast, when a triad member explains that students will be limited by cost during a classroom design activity, this is not a case of explicit NOE instruction; while an implicit NOE message is being communicated, no overt reference is being made to the engineering discipline. The identified instances of explicit NOE instruction were associated with their relevant disciplinary features of engineering, and these were assembled into a cross-case meta-matrix to facilitate the development of conclusions (Miles & Huberman, 1994).

To describe the implicit NOE messages communicated by each triad, the analysis strategy was to first characterize the consistent elements of engineering instruction for each triad. Drawing from the situated cognition perspective (Brown, Collins, & Duguid, 1989), if students participate in engineering activities that are structurally consistent, they are likely to form associations between those consistent structures and the field of engineering. After identifying the consistent structural elements of the engineering lessons of each triad, they were associated with the NOE features shown in Figure 1, then were assembled into a cross-case meta-matrix to facilitate further analysis (Miles & Huberman, 1994).

Research Question 2 focuses on the NOE messages the triads intended to communicate, and which ones they thought they communicated. Data for this question were drawn from formal and informal interviews with participants as well as planning documents. Analysis of these data focused on the learning objectives that were stated by participants during informal interviews, listed on planning documents, or indicated within the classroom (e.g., learning targets written on the board). After compiling the learning objectives for each engineering lesson, NOE-related learning objectives were identified, and summaries for each triad were then produced that identified the main NOE ideas that they intended to communicate to students. The summaries were then compared to the NOE messages identified by Research Question 1.

Like Research Question 1, the triad was treated as the unit of analysis for Research Question 2. Informal interviews were typically conducted with triad members in a group setting, correspondence was addressed to the whole triad rather than individuals, and planning documents were taken to reflect the work of the whole triad rather than a single member. Individual voices were present in the interviews and correspondence, but the three triad members were typically in agreement regarding the objectives for engineering lessons. When they did occur, disagreements between triad members related to the relative emphasis of multiple learning objectives rather than which learning objectives were present. To handle these disagreements, when identifying the learning objectives for each engineering lesson, all stated (either verbally or in writing) objectives were listed, regardless of their relative emphasis.

Findings

Question 1: What NOE Messages Were Conveyed to Students During Engineering Instruction?

While all triads implemented engineering lessons with their students, the quantity and characteristics of those lessons varied across the triads. Table 4.4 summarizes the engineering lessons taught by each group during the semester. The table indicates the total number of minutes of engineering lessons that were observed for each triad. Observations could not be conducted for every engineering lesson, so the time observed gives only a lower bound of the time each triad devoted to engineering instruction during the semester. Based on correspondence with participants, the actual total time spent on engineering instruction for each triad was no more than 50% more than the time observed. These times also provide a relative sense of the quantity of engineering instruction implemented by each triad compared to one another.

The engineering lessons listed in Table 4.4 are presented in chronological order, but the time between each lesson varies. For Triad 4, for example, the time between the introductory lesson on engineering and the beach erosion design activity was approximately 8 weeks. In contrast, the time between the first two engineering lessons of Triad 2 was only 1 week. Many of the engineering lessons were design activities; in these instances, Table 4.4 indicates the problem scenario presented to students as well as salient characteristics of the activity (e.g., whether the design activity explicitly followed the steps of an engineering design process [EDP] model, or whether the design activity used a rubric to evaluate the performance of students' designs). For engineering design lessons, Table 4.4 also indicates whether the source of the activity was a known curriculum such as *Engineering is Elementary (EiE)*. For other types of engineering lessons, Table 4.4 provides a brief description of the classroom activities.

Table 4.4: Summary of Engineering Lessons Implemented by Each Triad

Triad 1	Triad 2	Triad 3	Triad 4
Time Observed: 685 minutes	**Time Observed: 700 minutes**	**Time Observed: 445 minutes**	**Time Observed: 225 minutes**
Parachute – Design Task: Plan and construct a parachute from limited materials that will allow a load to land safely. -One revision cycle -*EiE* curriculum	**Tower - Design** Task: Plan and construct the tallest tower given limited materials. -No other explicit criteria/constraints	**Introduction to Engineering Lesson** Presentation on what engineering is in general terms, and watched a short video describing the difference between science and engineering.	**Introductory Presentation** On the first day with students, the engineer showed a presentation that described his field of engineering and the sort of work that he does.

Table 4.4 continued

<u>Job Classification Lesson</u> Students were given job descriptions and were tasked with sorting them into similar categories. Eventually, these categories were labeled as "scientist" and "engineer," and each were defined. (NOTE: This lesson was revisited later in the semester)	**<u>House - Design</u>** Task: Plan and construct a small house out of cardboard that can withstand wind created by a fan. -Consider material cost -Performance rubric -One revision cycle	**<u>Sea Wall – Design</u>** Task: Plan and construct a wall from limited materials that will protect a model beach from erosion. -Explicit reference to EDP -Consider material cost -Performance rubric -One revision cycle	**<u>Beach Erosion – Design</u>** Task: Plan and construct a way to limit the erosion of a model beach using limited materials. -Explicit reference to EDP -Consider material cost -Performance rubric -One revision cycle
<u>Mars Rover – Design</u> Task: Create a plan for a Mars rover that takes into account the features of the Martian surface. -No limit on materials -Planning only	**<u>Hexbug - Design</u>** Task: Plan and construct a maze for an electronic "bug" to travel that meets some specifications. -Consider material cost -Strict time limit	**<u>Wind Turbine – Design</u>** Task: Plan and construct a rotor for a wind turbine, using limited materials, that will spin as fast as possible when put in front of a fan. -Explicit reference to EDP -Performance rubric -One revision cycle	
<u>Mars Rover Coding</u> Students learned how to use a set of commands that remotely controlled a robot, and had to create a code that would guide the robot along a set path over "mars-like" terrain.	**<u>Plant Package – Design</u>** Task: Plan and construct a package that will transport a plant and keep it healthy. -Explicit reference to EDP -Consider material cost -Performance rubric -One revision cycle -*EiE* currriculum	**<u>Tower – Design</u>** Task: Using limited materials, construct the tallest stable tower in the time allotted. Activity occurred 3 times, each with different materials (e.g., gumdrops and spaghetti). -Strict time limit	
<u>Tower – Design</u> *Details Unclear* – grew out of a math problem in which students had to decide how to place windows in a building. They later planned and built a physical model building.	**<u>Bridges Lesson</u>** Students researched beam, arch, suspension, truss bridges; findings presented to the rest of the class	**<u>Egg Drop – Design</u>** Task: Plan and construct a way to keep a dropped egg safe using limited materials. -Explicit reference to EDP -Rubrics unknown -One revision cycle	
<u>Defining Technology</u> Students classified objects as technology or not-technology, then discussed how they might define technology. They eventually are given a definition for technology, and technology is linked to engineering.	**<u>Paper Bridge – Design</u>** Task: Plan and construct a bridge that will span a set distance using only paper and glue.	**<u>Virtual Lab Tour</u>** Via video call, students were given a tour of the engineer's lab, and he explained the work that he does in the lab.	

Table 4.4 continued

<u>Oil Spill – Design</u> Task: Plan and carry out a method for cleaning a model oil spill using limited materials. -Explicit reference to EDP -Consider material cost -Part of a revision cycle -Performance rubric -*EiE* curriculum	**<u>Toothpick Bridge – Design</u>** Task: Plan and construct a bridge using toothpicks and glue that will span a set distance and be as strong as possible. -Explicit reference to EDP -Precise diagrams required -Consider material weight	**<u>Circuit – Design</u>** Task: Create a schematic for a circuit using basic components that will cause a light to turn on when a switch is activated, then build the circuit. -Schematics given to other students to construct -Schematics tested using simulation software -*EiE* curricilum	
	<u>Catapults – Design</u> Task: Using limited materials, plan and construct a device that will launch a small object a set distance. -Additional criteria/constraints unknown		
	<u>Maglev Train – Design</u> Task: Design and construct a magnetic track and a cart that will levitate above the track. -Consider material cost -Performance rubric -*EiE* curriculum		

Explicit NOE Instruction

As shown in Table 4.4, of the relatively few cases of *non*-design engineering lessons implemented by triads, most primarily targeted the NOE (or, in the case of the “Defining Technology” lesson of Triad 1, the nature of technology). The exception was the “Bridges Lesson” implemented by Triad 2, which focused on engineering concepts related to bridges. While some lessons were devoted to explicit NOE instruction, other instances of explicit instruction also occurred within the context of design activities. The NOE was typically addressed either at the beginning or the end of a design activity. For instance, at the conclusion of the “House – Design” lesson implemented by Triad 2, students were asked “why engineers need to consider costs when they do their work." The students had just reflected on their own attempts to minimize the costs of their designs, and the triad made the connection to real engineering work explicit with that question, along with the ensuing discussion of students' ideas. Another example occurred in the "Beach Erosion – Design" activity implemented by Triad 4. Here, the triad explicitly addressed the difference between engineering and science at the beginning of the lesson. The triad explained to students that the activity they were about to do was an engineering activity, not science. They clarified that "science is about learning about nature, like erosion, but engineering is about solving problems."

Table 4.5 summarizes the explicit NOE instruction delivered by each triad. For each of the disciplinary features of engineering, Table 4.5 provides the explicit messages communicated to students by the triads. Note that triads did not explicitly address all nine features, and several features were not addressed by any of the triads. The features of engineering were addressed to varying extents by the four triads. For instance, Triad 1 devoted a whole lesson to helping students understand the differences between scientists and engineers. Triad 4, in contrast, addressed this idea with a brief statement at the beginning of a design activity. To capture these differences, Table 4.5 indicates the features that were given emphasis by each triad. Emphasized features were addressed for an extended period of time during a single lesson, or were addressed multiple times across multiple lessons.

Table 4.5: Features of Engineering Explicitly Addressed by Triads

NOE Feature	Triad 1	Triad 2	Triad 3	Triad 4
Design in Engineering	**Mentioned** Testing is an important part of design, and failure is common. **Emphasized** Technologies are the products of engineering design.			

Table 4.5 continued

Specifications, Constraints, and Goals		**Mentioned** Engineers must consider costs when they do their work.		**Mentioned** Engineers must consider costs as part of their designs.
Sources of Knowledge				
Knowledge Production			**Emphasized** Engineers can work in labs and engage in research activities.	
Scope of Engineering				**Emphasized** Aerospace engineers work on the design of aircrafts and space vehicles.
Models of Design Processes	**Mentioned** Engineering design involves a sequence of steps, although they can be done out of order.	**Emphasis** Engineering design involves a sequence of steps in a specific order.	**Emphasis** Engineering design involves a sequence of steps in a specific order, although it can be iterative.	**Mentioned** Engineering design involves a sequence of steps in a specific order.
Cultural Embeddedness				
Internal Culture of Engineering	**Mentioned** Engineers have to be perseverant, as their designs rarely work the first time.		**Mentioned** Engineers have to be perseverant, because design is challenging	
Engineering and Science	**Emphasized** "Scientists study, engineers use science to help create something new or improve something that already exists."		**Mentioned** Science is learning about nature, whereas engineering is about solving problems using science	**Mentioned** Science is learning about nature, whereas engineering is about solving problems using science.

Overall, the four triads explicitly addressed NOE ideas infrequently, and the vast majority of engineering instruction consisted of engaging students in design activities. While NOE ideas were occasionally explicitly addressed during these lessons, such instances were typically brief (often less than one minute, rarely more than three). Exceptions to this pattern occurred when triads devoted lessons specifically to learning about the NOE; each triad except for Triad 2 implemented at least one such activity.

Triad 1 stands out as an unusual case in that they devoted two lessons to learning about the nature of engineering and the nature of technology. Table 4.6 provides the total time observed for each triad along with the observed time that each triad devoted to explicit NOE instruction. As seen in Table 4.6, Triad 1 devoted substantially more class time than other triads to explicit instruction in the NOE or the nature of technology. In contrast, the other three triads were observed to explicitly address NOE ideas for less than an hour over the entire semester. Triad 1 did not necessarily address more features of engineering than other triads, but they did address them in much greater depth.

Table 4.6: Time Observed Per Triad and Time Devoted to NOE Instruction

	Triad 1	**Triad 2**	**Triad 3**	**Triad 4**
Total Time Observed	1135 minutes	1110 minutes	600 minutes	360 minutes
Time Observed for Engineering	685 minutes	700 minutes	445 minutes	225 minutes
Time Observed for Design Activities	380 minutes	555 minutes	405 minutes	190 minutes
Time Observed for Explicit NOE	230 minutes*	25 minutes	40 minutes	25 minutes
% of Observed Engineering Instruction Devoted to Explicit NOE	33%*	4%	10%	11%

**Includes lessons addressing the nature of technology*

Implicit NOE Instruction

As shown in Table 4.4, design activities were the most common form of engineering instruction among the triads. Not only were these activities more common than non-design activities, they also tended to be much longer. A few design activities were completed within a 45-minute class period (e.g., the tower design activities of Triad 3), but most spanned multiple days, with some occupying 120 minutes of class time or more (e.g., the beach erosion design activity of Triad 4, which ran for one full week). The NOE was rarely addressed explicitly during design activities; the triads typically labeled design activities as “engineering” rather than “science,” and occasionally indicated that students were “acting as engineers” during the activities. Design activities were primarily sources of *implicit* NOE instruction. Implicit NOE messages were sent to students through the way that design lessons were structured and the nature of the activities in which students were engaged. Given the substantial amount of time during which students were engaged in design activities (see Table 4.6), these activities had the capacity to significantly influence students’ NOE views.

To better understand the NOE messages communicated to students by these activities, common structural features of the design activities were identified. While they varied with respect to certain details, all the design activities implemented by each triad showed a common underlying structure. The common structure matched that of the engineering lesson modeled for project participants during the professional development workshop, as well as that found in engineering curricula such as *Engineering is Elementary* (Museum of Science, Boston), which were often utilized by triads (see Table 4.4).

Table 4.7 summarizes the underlying structure of triads’ engineering design activities. The table indicates the sequence and common features present in all observed design activities. Design activities varied in certain respects, and the third column of Table 4.7 describes additional elements that were often observed in the activities but were not present in all. The third column indicates the percentage of observed lesson across all triads that included each element. The sequence of steps that occurred in each observed design activity is related to representations of the engineering design process (EDP) that were often used in classrooms. During interviews, nearly all triad members explained that good engineering activities include all of the steps in the EDP. Triads often presented the EDP to students as a cycle of steps in a flowchart, with typical steps including: asking about the problem, brainstorming, planning, building, testing, and improving (i.e., returning to the beginning of the cycle). As indicated in Table 4.4, many of the engineering design activities explicitly referenced an EDP model, often at the beginning and end of the activity.

Table 4.7: Common Structure of Engineering Design Lessons

Lesson Stage	Elements Present in All Lessons	Common Additional Elements
1) Introduce Scenario	-Teachers explain what students are expected to produce, and what goal the product is to achieve	-Teachers present a context for the activity (e.g., a story) (60%)
2) Specify Constraints	-Teachers indicate available materials -Teachers provide details about the specific outcome the designs are to achieve (e.g., a tower of specific height)	-Teachers present evaluation rubric (60%) -Costs assigned to materials; constrained on total cost (70%) -Time limitations imposed (20%)
3) Planning	-Students work in teams -Students sketch plans individually -Students create a group plan that includes ideas from each member	-Teachers must approve students' plans (50%)
4) Building	-Students build their idea based on what they drew as a group	-Explicitly limited building time (50%)
5) Testing	-Products of building are subjected to a testing procedure	-Testing done publicly (80%) -Numerical score determined for product (70%)
6) Reflection & Revision	-Students think about what worked well and what did not.	-Reflections discussed with class (50%) -Students create revised plans (50%) -Students build/test redesigns (40%)

The lesson structure shared by all engineering lessons in Table 4.7 implicitly communicated much about the NOE. Because students were consistently made aware that they were participating in engineering design, and because these activities followed a consistent structure, they represented powerful avenues for communicating implicit NOE messages. Triad 4 represents an exception in that students only participated in one engineering design activity; in this case, the implicit NOE messages were likely less powerful as they were not reinforced over multiple lessons. Table 4.8 indicates the implicit NOE messages that were communicated to students, and links these to the design activity elements that conveyed the NOE message.

Table 4.8: Implicit NOE Messages Communicated Via Engineering Design Activities

Implicit NOE Message	Source of Message	Related NOE Feature
Engineering design is done in teams	Students work in teams during design activities	(1) Design in Engineering
The product of engineering design is a tangible object; plans are a tool to help engineers produce the object	The goal of an engineering design activity is a working physical product	(1) Design in Engineering
Engineers' products are evaluated by an external agent in a public setting	Students' products are tested and evaluated by teachers in front of the class	(1) Design in Engineering
Engineers are constrained by available materials, costs, and time	Students had a limited set of materials from which to choose, which often had associated prices; planning and building had to be completed within the class period	(2) Specifications, Constraints, Goals
The goals, specifications, and constraints are given to engineers by an external agent	Teachers provided goals, specifications, and constraints to students	(2) Specifications, Constraints, Goals
Specifications and constraints are rigid	Students had to adhere to the constraints or specifications	(2) Specifications, Constraints, Goals
Engineers are involved in both the planning and the production of products	Students created plans, but also physically constructed the planned objects	(5) Scope of Engineering
Engineering follows a rigid series of steps	Students first learned about the problem, then created plans, then built, then tested, then revised – in that order	(6) Models of Design Processes
Engineering differs from science: engineering is concerned with the creation of products, where science is not	Students were aware that they were doing engineering (not science) when they were planning and creating products.	(9) Engineering and Science

The NOE messages described in Table 4.8 were derived from the universal elements of engineering design activities, along with the elements present in a high proportion of activities. Note that Table 4.8 does not separate the implicit messages by triad, as the design lessons implemented by each triad (and thus the implicit NOE messages communicated by each) were more alike than they were different. The NOE features noted in Table 4.8 are primarily those that are directly related to engineering design. This is not surprising, given that the implicit NOE messages were being communicated in the context of *design* activities. Students, for instance, never engaged in any form of engineering research, and so the lack of NOE messages related to Knowledge Production in Engineering is unsurprising.

Accuracy of Explicit and Implicit NOE Instruction

Having described the NOE ideas that were explicitly and implicitly communicated by the four triads, a crucial question is the extent to which those ideas *accurately* reflect the NOE. For the most part, the NOE ideas that were explicitly addressed by the triads were accurate. Many of the ideas were superficial and highly simplified, but this is not surprising given the age of the students. The only potentially problematic idea is related to models of the engineering design process (EDP). All triads presented the EDP as a series of steps that engineers use during their work. Triads 1 and 3 further qualified the EDP by pointing out that the steps do not necessarily occur in a specific order. Even with those qualifications, the notion that a flowchart EDP model can be used to *describe* engineering work is questionable. Such EDP models can be useful as a learning tool for novice designers, but cannot be used to generally describe the work of expert designers (Bucciarelli, 1994; Dorst & van Overfeld, 2009; Kroes, 2012; Mitcham, 1994)

The implicit NOE messages conveyed by the triads were mixed in terms of accuracy. Reasonable ideas implicitly communicated by the engineering design lessons included: engineers work in teams, engineering design takes place under constraints, and engineering design is unlike science. These accurate ideas all exist at a high level of generality; when more specific NOE messages are considered, their accuracy becomes more questionable. First, students were given the sense that the specifications and constraints for engineering design are given by an external agent (the teacher, in the case of the classroom activities), and that these are non-negotiable. To some extent, engineers are given goals, specifications, and constraints by external entities such as clients or governments (in the case of regulations). However, these are often vaguely stated, and engineers spend considerable time interpreting goals and specifications, formulating them quantitatively, and in many cases renegotiating them; specifications and constraints are not necessarily rigid (Bucciarielli, 1994; de Vries, 2009; Dym & Brown, 2012; Vincenti, 1990).

Second, classroom engineering lessons placed much emphasis on physically building technological objects. Engineers need to consider production when designing a technology, but they are not highly involved with the physical assembly of objects. Engineers often produce physical prototypes and models, but these are primarily used to test and evaluate their designs; the prototypes and models are not themselves the products of engineering work (Dym & Brown, 2012; Kroes, 2012; Mitcham, 1994; Petroski, 1996). Notably, in many of the classroom engineering activities, students produced objects that could be potentially be considered models. For example, Triad 2 had students construct a bridge out of toothpicks that could span a two-foot distance. Although the bridges that students produced might resemble models in that they are small representations of actual structures, they did not serve as genuine models in the classroom. The small bridges were not functional versions of designs for real bridges; instead, the small bridges were themselves the products. This was the case for all classroom activities in which objects were produced by the students.

Third, planning was not accurately represented during the engineering activities. Triads emphasized the importance of planning and a consistent requirement given to students was that they have a plan before obtaining materials to construct their idea. Students' plans had to specify which (and how many) materials they required from a "store" that was run by one of the triad members; only after identifying specific materials could they be obtained. Students complied with the planning requirements, but typically did not closely follow their plans once their materials were obtained. Most often, students' plans were closer to sketches than designs, and thus could not be followed closely. Once students obtained materials, they quickly started to improvise to make the materials work as desired. The end products of the classroom design activities were the tangible objects that the students created. Students' plans were merely stepping stones en route to the "real" objective of creating a functioning product. Even though the structure of the classroom engineering activities placed value on planning, students' actual planning practices indicated that these were not terribly important.

The low value that students placed on their design plans in the present study parallels findings from prior research on students' design practices (Mawson, 2003). Most importantly for the present work, the way planning was treated within classroom activities misrepresents the NOE. For most engineering design work, the *plans* are the end products of the design process. Engineers create precise plans that specify the physical form of a technology, and often provide details for how that technology ought to be produced (Dym & Brown, 2012; Kroes, 2012). While engineers do create physical prototypes, these are generally used as physical manifestations *of design plans*, and are used so that the *plans* can be subjected to physical testing (Vincenti, 1990). In authentic engineering practice, prototypes are subordinate to the plans that specify them; in the classrooms in the present study, plans were subordinate to the physical products.

The problematic implicit NOE messages discussed above ultimately relate to the degree to which the classroom engineering activities reflected *authentic* engineering practice. The classroom design activities reflected genuine engineering practice in certain respects, but in many others they were “ersatz” (Brown, Collins, & Duguid, 1989). Of course, engineering in the classroom is unlikely to be able to replicate actual engineering work, especially at the elementary school level. The distance between classroom practice and genuine disciplinary practice, however, is important to consider given current rationales for engineering in K-12 schooling, and the ways that classroom activities can convey the NOE.

Question 2: How did the NOE messages that were actually conveyed compare with what participants intended to convey about the NOE?

The triads in the present study communicated a range of NOE ideas to students, and this question focuses on the extent to which the triads *intended* to convey those ideas. Table 4.9 summarizes the NOE-related learning objectives that were targeted by each of the triads over the course of the semester. Some of the listed learning goals were pursued only during a single lesson, and others were recurring goals over the whole semester. Table 4.9 separates the NOE learning objectives into two categories: explicit and implicit. The triads did not differentiate their learning outcomes using these constructs; the categorization instead reflects how the triads’ learning goals are related to the NOE. The explicit learning objectives are ideas that are directly tied to describing the structure of the engineering discipline. The ways in which science and engineering differ, for instance, directly describes the NOE. In contrast, the implicit objectives are not directly tied to the engineering discipline. All triads, for instance, described how their students learned about the importance of constraints when doing design, and three of the triads discussed how their students learned the importance of planning during design. However, the triads did *not* specify that their students learned how constraints are important *to engineers*, or that planning is important *to engineers*. By pursuing these learning objectives, the triads were, at most, addressing the role of constraints and planning *in engineering* only implicitly.

Table 4.9: Engineering Learning Objectives Targeted by Each Triad

	Triad 1	**Triad 2**	**Triad 3**	**Triad 4**
Explicit	*The difference between science and engineering *What technology is and how it is connected to engineering *The steps of the EDP	*The steps of the EDP	*The difference between science and engineering *The kind of work that engineers do *The steps of the EDP	*The kinds of work that engineers do *The steps of the EDP
Implicit	*The importance of constraints	*The importance of criteria and constraints *The importance of planning and revision	*The importance of criteria and constraints *The importance of planning and revision	*The importance of criteria and constraints *The importance of planning and revision

The explicit NOE ideas that were targeted by the triads are well aligned with the explicit instruction summarized in Table 4.9. All triads discussed how they wanted students to learn the steps of the EDP, and their instructional practices reflected that goal. Similarly, the triads that wanted students to get a sense of the difference between science and engineering (Triads 1 and 3) or a sense of what engineers do (Triad 4) also explicitly conveyed those ideas during instruction. In fact, the triads explicitly addressed *more* NOE ideas than they addressed during their discussions of learning objectives. Those additional NOE ideas were often represented in planning documents, so their omission during the discussions of learning objectives likely indicates that those NOE ideas were not regarded as the *primary* learning objectives for the given lesson. Overall, for the case of explicitly addressed NOE ideas, there was high alignment between what the triads intended to convey and what they actually communicated to students.

In terms of implicit NOE ideas, all of the triads intended to convey to students the importance of constraints within engineering design, and this was indeed communicated to students via engineering design activities (see Table 4.8). Three of the four triads also intended for students to learn the importance of planning, but the extent to which this occurred was less clear. All of the triads required their students to plan before being able to build their ideas, indicating the importance that the triads placed on this part of the process. Yet the structure of the activities was such that planning was merely a stepping stone to the "real" work of physically producing a working product; this aspect of the activities tended to undermine the triads' goals of conveying the importance of planning.

As shown in Table 4.8, the triads communicated many more implicit NOE messages than they intended. Many of the unintended implicit NOE messages were also problematic in terms of their accuracy. As discussed above, the classroom engineering activities differed from authentic engineering practice in substantial ways, yet with few exceptions the triads did not generally seem to be aware that this was the case. The triads largely regarded their engineering lessons as reflective of genuine practice; when asked how their classroom activities differed from the work of real engineers, most participants identified only superficial differences.

Several exceptions to this pattern are noteworthy. Triad 1 consistently showed concern for the authenticity of their engineering design lessons throughout the semester, demonstrating a clear awareness of the implicit messages they might be sending to students. Unlike the other triads, Triad 1 implemented several lessons that were about engineering, but not in the form of design challenges. A reason that the triad members gave for this was that they often found the design activities to not be as authentic as they desired. Although they implemented several design activities during the semester, the triad members were not satisfied with the way that these represented the field to their students. Triad 2 also showed some awareness of the potentially problematic messages sent by their engineering activities. Midway through the semester, the members of Triad 2 started to worry that, because building was such a salient part of their engineering activities, their students would erroneously associate engineering with building. While they were not able to find a way to address this concern, they nevertheless indicated an awareness that their lessons might be implicitly communicating inaccurate ideas about the NOE. Triads 3 and 4 did not communicate these sorts of concerns.

Discussion

The present study sought to understand the NOE instructional practices of participants in a professional development project, as well as the intended practices of those participants. The four triads examined in this study communicated the NOE to their students through both explicit and implicit means. While the NOE ideas they addressed and the extent to which they addressed them varied, all of the triads chose to explicitly teach the NOE, and all triads identified NOE ideas among their engineering learning goals for students.

Explicit NOE instruction was encouraged during the project's professional development workshops, and the engineers received support for engineering instruction, including explicit NOE instruction, during their on-campus seminar. Given these influences, the fact that participants did, in fact, explicitly teach the NOE is not surprising. However, past research on the nature of science (NOS) has shown that even when teachers experience extensive instruction in the NOS, even when teaching the NOS is strongly encouraged, and even when teachers express intentions to teach the NOS, many never address it with students (Abd-El-Khalick, Bell, & Lederman, 1998; Lederman, 1999; Lederman & Lederman, 2014). Given the challenges in getting teachers to adequately address the NOS, what might account for the relative willingness of participants in the present study to address the NOE? The professional development project might be particularly effective in terms of promoting NOE instruction; the presence of an engineer in the classroom, for instance, might strongly encourage discussion of the engineering discipline so that students will understand what that engineer does. Alternatively, engineering education might more readily lend itself to addressing the NOE. Especially at the elementary level, no pressure exists to cover specific engineering *content*, which might free them to address NOE issues with students (Custer, Daugherty, & Meyer, 2010; Daugherty & Custer, 2012).

The triads' explicit NOE instruction was positive but, excepting Triad 1, it was also infrequent. Most of the NOE instruction delivered by the triads was implicit, and the analysis of this mode of instruction revealed that the implicit NOE messages were often problematic. These problems arose because of the distance between the classroom engineering activities employed by the triads and genuine engineering practice. The triads intended to provide students with *authentic* engineering experiences, but those experiences fell short in a variety of ways. Framing this in terms of a situated perspective on learning: students were given opportunities for legitimate peripheral participation in a community of practice that resembled engineering in certain ways, but ultimately the community was one of "classroom engineering" rather than authentic engineering (Brown, Collins, & Duguid, 1989; Lave, 1997; Lave & Wenger, 1991). As a result, students were given a distorted sense of the NOE.

Overall, the triads did not help students understand the ways in which classroom engineering differs from real engineering; indeed, the triads generally failed to acknowledge those differences. This was true despite the fact that the engineers in the triads contributed to the planning of the lessons and were present during much of the instruction. Perhaps more striking than the explicit NOE instruction that *did* occur in the classrooms were the many opportunities for explicit instruction that were *missed*, especially by the engineers. The engineers were in an ideal position to help students relate what they did during classroom activities to the real work of engineers, yet they routinely failed to do so. Perhaps the engineers did not recognize that this was something worth doing with students, although this is unlikely given that explicit NOE instruction was addressed during their on-campus seminar. Alternatively, the engineers might not have felt pedagogically empowered to address ideas with students, instead deferring to the teachers in their triads. Another possibility is that the engineers failed to accurately evaluate the classroom engineering activities in terms of how they related to authentic engineering work. As shown in Chapter 2, the engineers might not be much more knowledgeable about the NOE than the teachers in the triads. Without sufficient NOE knowledge, the engineers would have been unable to seize upon the explicit NOE instruction opportunities that arose during lessons.

Implications

Many policy documents advocate for improving students' understanding of the NOE as part of K-12 engineering education efforts (NAE & NRC, 2008, 2009; NRC, 2012, 2014). Despite these calls, studies examining the NOE in K-12 education are few, and fewer still are NOE-related studies of classroom practices. The present study provides a first step toward understanding how the NOE is communicated during engineering instruction, and it raises important issues regarding how to more effectively convey the NOE to students. As noted above, the classroom engineering activities employed by participants in this study did not accurately communicate the NOE. While these results are confined to the context of the professional development project under study, the engineering activities that triads implemented were not atypical; many of the activities were drawn from established curricula such as *Engineering is Elementary* (Museum of Science, Boston). This study therefore raises concerns for elementary-level engineering design activities *in general*. The following should be asked of *any* engineering design activity used in the classroom: in what ways does this activity resemble and not resemble genuine engineering practices, and what messages does it therefore convey about the NOE?

Even under the best circumstances, classroom engineering activities will differ from authentic engineering practice in substantial ways, just as is the case for classroom science activities (Abd-El-Khalick et al., 2004), which indicates the importance of explicit instruction in the NOE. Just as explicit NOS instruction can help students form a conceptual bridge between classroom science activities and real scientific work (Bell, Mulvey, & Maeng, 2016; Clough, 2006), so too can explicit NOE instruction play a crucial role in overcoming the limitations of classroom engineering activities. The results from this study indicate that elementary teachers are willing to explicitly address the NOE with their students. Moreover, if teachers are aware of the shortcomings of engineering design activities (as was the case with Triad 1), they might be more willing to use explicit NOE instruction to fill in the gaps.

The present study provides insights into classroom NOE practices, but has several limitations. This study examines the instruction of participants in an intensive professional development project, but most elementary teachers never receive such support (Banilower et al., 2013). As engineering becomes more common in classrooms (Moore et al., 2014), an important question is how elementary teachers who do *not* receive professional development will portray the NOE to students. Future work is needed in this area. Another limitation of the present study is that it did not examine how triads' instruction impacted students' NOE knowledge. While the analyses point to many NOE messages that were conveyed to students, how students interpreted those messages is a question that was beyond the scope of the present work. Future work should be directed at better understanding how students develop their understanding of the NOE.

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CHAPTER 5. CONCLUSIONS AND IMPLICATIONS

Review of Major Findings

The present work was motivated by the goal of promoting students' understanding of the NOE, a goal which has been consistently stated by those who advocate for engineering in K-12 education (e.g., ITEA, 2007; Lachapelle & Cunningham, 2014; Moore et al., 2014a; NAE & NRC, 2008; NRC, 2012). To achieve this goal, teachers must be prepared to accurately communicate the NOE to their students during instruction. The three studies presented here sought to investigate aspects of elementary teachers' nature of engineering (NOE) knowledge and practices within the context of a professional development project focused on preparing preservice and in-service teachers to teach science and engineering (see Chapter 1 for a description of the project). Together, they begin to provide an understanding of how elementary teachers can meet the goal of accurately communicating the NOE. The results from each study are summarized below.

Study 1: The Development of Elementary Teachers' Knowledge of the Scope of Engineering

This study examined elementary teachers' knowledge of the *scope of engineering* (SOE), an important NOE dimension. It also compared the knowledge of the teachers in the research project to that of the engineers with whom they worked. The research questions addressed by this study were:

1) How can project participants' SOE knowledge be measured?
2) What differences, if any, exist in teachers' knowledge of the scope of engineering before and after participation in this project?
3) How do the teachers compare to the engineers in terms of scope of engineering knowledge before and after participation?

Addressing the first question required developing an instrument to measure SOE knowledge, which was done by analyzing and refining an existing survey, which yielded a set of suitable SOE items. This study found that all project participants, teachers and engineers, improved their SOE knowledge over the course of the project. More specifically, participants were better able to accurately categorize non-engineering activities as unimportant for engineers. A surprising result was found for the third research question in that the engineers in the study performed no better than the teachers on the SOE instrument, either on the pretest or posttest. This indicates that engineers might not necessarily be experts in the NOE.

Study 2: What Does "Learning About Engineering" Mean to Teachers?

This study investigated how participants in the research project described what their students learned about engineering over their semester of participation. Participants discussed their students' learning in exit interviews and their responses were categorized according to whether they discussed students' learning of engineering concepts, practices, the NOE, or affective outcomes (see Figure 3.1). The study addressed the following research questions:

1) When participants in the professional development project described what students learned about engineering, which learning outcome domains did they discuss?
2) To what extent, if any, did the engineers view what students learned about engineering differently than the cooperating teachers and student teachers?

Few participants in the study discussed students' learning of engineering concepts or affective outcomes. The inattention to engineering concepts is not surprising given their scant attention in the literature (Custer, Daugherty, & Meyer, 2010; NRC, 2014). In contrast, participants often discussed students' learning of engineering practices and the NOE. The relatively high frequency with which NOE outcomes were discussed was a surprising finding, given the well-documented challenges in getting teachers to address the nature of science (NOS) with students. The finding indicates that the teachers in the study were more attentive to the NOE than would have been initially expected. In relation to the second research question, the patterns of responses for the teachers and the engineers in the study were much the same.

Study 3: Elementary Teachers' Portrayals of the Nature of Engineering

This study provided an in-depth examination of the engineering instruction delivered by four triads who participated in the research project. The goal of the study was to characterize the ways in which the triads both explicitly and implicitly communicated the NOE to their students during engineering lessons. The research questions for this study were:

1) What NOE ideas were explicitly and implicitly conveyed during engineering instruction by the triads in the professional development project?
2) How did the NOE ideas that were *actually* conveyed by the project participants compare with what the triads *intended* to convey?

This study found that all four participating triads explicitly addressed the NOE with their students, although they did so to varying degrees. Three of the triads made only brief efforts to explicitly address the NOE, while the fourth devoted considerable class time to explicit NOE discussions. The NOE messages communicated via explicit instruction were accurate, and coincided with what the triads intended to convey to students about the NOE. All four triads communicated similar implicit messages about the NOE, because the way that engineering design lessons were structured was very similar across triads. The repeated use of the common instructional model implicitly sent consistent messages to students about the NOE. Some of those NOE messages were reasonable, but others conveyed a distorted sense of the NOE, and were often at odds with what the triads intended to convey to students.

Broader Findings Across All Three Studies

Together, the studies presented here indicate that when elementary teachers were given support via the project's professional development workshops and partnerships with content area experts (in this case, engineering graduate students), several positive outcomes were obtained with respect to teaching the NOE:

1) Elementary teachers' NOE knowledge was improved
2) Elementary teachers value the NOE as a learning objective
3) Elementary teachers explicitly address the NOE with students in accurate ways

Given elementary teachers' limited preparation in engineering (Banilower et al., 2013), these are valuable outcomes for effectively conveying the NOE during elementary engineering instruction. The first two outcomes are prerequisites for accurate NOE instruction. As research on the nature of science (NOS) has indicated, teachers must not only understand the NOS but value it as a learning objective if they are to successfully teach it in their classrooms (Abd-El-Khalick, Bell, & Lederman, 1998; Herman, Clough, & Olson, 2013, 2017; Lederman, 2007; Lederman & Lederman, 2014). Therefore, the fact that elementary teachers valued the NOE as a learning objective is promising for NOE instruction. The third outcome is particularly encouraging given that NOS research has consistently documented challenges in getting teachers to explicitly address the NOS with students (Abd-El-Khalick, Bell, & Lederman, 1998; Lederman, 1999; Lederman & Lederman, 2014).

The studies presented here also identify substantial challenges in promoting NOE instruction in the elementary classroom. While the teachers in the Chapter 4 study did explicitly address the NOE with students, they did so infrequently. More importantly, many of the implicit NOE messages that were conveyed to students were inaccurate, and many of the teachers were unaware of the inaccuracies that were present. This was true even though, as found in the Chapters 2 and 3 studies, the teachers improved their NOE knowledge during the project and valued the NOE as a learning goal. Moreover, NOE instruction was problematic even though each teacher in the present work had an engineer in the classroom to aid in both planning and instruction. Despite the support structure that was in place, why did effective NOE instruction remain elusive?

One possibility is that, as found in Chapter 2, the engineers might be experts in their engineering disciplines, but not necessarily in the NOE. If placing engineers in elementary classrooms is to facilitate NOE instruction, then the engineers likely need additional preparation in the NOE, as well as how to teach it. The on-campus seminar that project engineers attended addressed the NOE to an extent, but to be effective, the course would likely need to expand its treatment of the NOE. For example, the seminar could help engineers critically evaluate classroom engineering activities for how they portray the NOE, and give them tools to engage students in discussions about how classroom activities are similar to and different from genuine engineering work. Related to this, the engineers need to be prepared to critically examine engineering curricula, such as *Engineering is Elementary* (*EiE,* Museum of Science, Boston). Although participants in the present work often developed their own engineering lessons, many were based on *EiE* lessons or utilized the instructional model of *EiE*. For example, a prominent component of *EiE* lessons is the 5-step representation of the “Engineering Design Process,” and this was a ubiquitous element of the engineering design lessons observed in Chapter 4. The engineers in the present study should have been able to identify the problems of such a representation of the design process. They did not, however, indicating that they need to be better prepared to appraise and modify published curricula, as well as appropriately raise potential issues with their teacher colleagues.

In broad terms, then, while the professional development project in the present work produced several positive outcomes related to NOE instruction in elementary classrooms, more would need to be done to make the teaching of NOE more accurate and explicit to students. Importantly, teaming engineers with elementary teachers is not enough to ensure that the NOE is accurately communicated in the classroom. Engineers need specific preparation to be effective communicators of the engineering discipline, as well as resources for NOE instruction.

Future Research

The work presented here suggests several lines of further research. A substantial limitation of the present research is that all three studies were conducted within the context of a professional development project that provided extensive support to elementary teachers to implement engineering instruction. Most teachers in the United States will never receive such support, if they receive any at all (Banilower et al., 2013). Despite limited preparation and minimal support, elementary teachers will increasingly be asked to teach engineering as more states adopt engineering standards for K-12 schools (Moore et al., 2014b). A crucial task for NOE research is to investigate the practices of teachers in the more typical scenario of minimal support, rather than on those in the relatively rare context of an intensive professional development project.

A second limitation of the present research is that it focused only on the elementary teachers rather than their students. Much was learned about how elementary teachers in the research project thought about and portrayed the NOE, but little is known about how students' views developed. Much more work is needed in this area so that teaching practices can be linked to the goal of improved student understanding of the NOE.

Finally, further research in the NOE demands the development of high-quality research instruments. The first study presented here made progress in this regard, but only for a single dimension of the NOE, and more work is yet needed even on that one dimension. Future instruments will need to be developed that can investigate knowledge of a variety of NOE dimensions, and be applicable for both teachers and students.

Implications for Education

If promoting students' understanding of the NOE is indeed a goal for K-12 engineering education, as argued by U.S. policy documents (e.g., NAE & NRC, 2008; NRC, 2012), the work presented here has several implications regarding how this goal might be pursued:

1. Engineering Design Activities Alone are Not Enough

K-12 engineering instruction often takes the form of engineering design activities. While these activities can promote many educational outcomes (Crismond & Adams, 2012; Lachapelle & Cunningham, 2014; NAE & NRC, 2009; NRC, 2014), they are not sufficient for providing students with an accurate picture of the NOE, as illustrated by the study in Chapter 4. Engineering activities in the classroom will necessarily differ from genuine practice in multiple ways, and these differences can convey inaccurate ideas about the NOE to students. Just as NOS research has consistently indicated the importance of explicit as well as implicit instruction (Lederman & Lederman, 2014), so too must the NOE be explicitly addressed with students. Explicit NOE instruction need not explore the full depth and complexity of the NOE, especially for elementary students, but teachers must help students understand the ways in which classroom activities reflect genuine engineering work as well as ways in which engineering work is distorted in the classroom.

2. Given Support, Elementary Teachers Can Explicitly Teach the NOE

Despite limited preparation in the discipline, this work found that elementary teachers are both willing and able to explicitly address the NOE with students when provided with sufficient support. However, support needs to be given to teachers in terms of NOE content knowledge, as this is a prerequisite for accurately addressing the NOE with students, and teachers are unlikely to have prior experience learning about the NOE. However, teachers must also be supported in terms of instructional practice; for instance, how NOE ideas can be discussed with students in the context of engineering design activities, or how the NOE can be taught in the context of a decontextualized activity. This support could be integrated into pre-service or in-service teacher professional development, as was done in the present work.

3. Implicit and Explicit NOE Messages Must be Coordinated

Explicit instruction in the NOE is crucial, but so too are the implicit NOE messages that students are conveyed to students during engineering activities. Elementary teachers must be aware of the implicit NOE messages that are being conveyed during instruction, and then leverage explicit instruction to draw attention to both the accurate and the problematic implicit messages. Doing this demands substantial NOE knowledge on the part of teachers, as they must critically examine the engineering activities that occur in their classrooms. Doing so also demands pedagogical skill to seamlessly integrate explicit NOE discussions into engineering instruction. Even with significant support, the teachers in the present work were not able to achieve this goal; importantly, most of the teachers were unaware of the implicit messages that they were communicating to students. To effectively coordinate implicit and explicit NOE instruction, teacher education and professional development efforts must help teachers understand the ways in which the NOE can be implicitly communicated during engineering activities, and also give them tools to engage students in conversations that compare and contrast classroom engineering activities with authentic practice.

4. Elementary Teachers Will Likely Struggle to Accurately Convey the NOE

Accurately communicating the NOE to students is extremely demanding; even when supported with engineers in the classroom, the NOE instruction of teachers in the present study was problematic in multiple ways. Compared to the participants in the present work, most elementary teachers are given far less support and preparation for teaching science and engineering (Banilower et al., 2013) compared to other subjects. As a result, as more students receive engineering instruction nationwide, they are likely to receive a distorted sense of the engineering discipline. Unless substantial resources are used to support *all* elementary teachers' instruction of engineering in general, and the NOE in particular, the goal of promoting students' accurate understanding of the NOE is not likely to be broadly attainable.

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APPENDIX A. INSTITUTIONAL REVIEW BOARD EXEMPT APPROVAL

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
1138 Pearson Hall
Ames, Iowa 50011-2207
515 294-4566
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Date: 6/27/2014

To: Dr. Joanne Olson
N131 Lagomarcino

From: Office for Responsible Research

Title: TEC-STEM Partnerships: Teachers and Engineers Collaborate for STEM in K-5

IRB ID: 14-336

Study Review Date: 6/26/2014

The project referenced above has been declared exempt from the requirements of the human subject protections regulations as described in 45 CFR 46.101(b) because it meets the following federal requirements for exemption:

- (1) Research conducted in established or commonly accepted education settings involving normal education practices, such as:
  - Research on regular and special education instructional strategies; or
  - Research on the effectiveness of, or the comparison among, instructional techniques, curricula, or classroom management methods.

The determination of exemption means that:

- **You do not need to submit an application for annual continuing review.**
- **You must carry out the research as described in the IRB application.** Review by IRB staff is required prior to implementing modifications that may change the exempt status of the research. In general, review is required for any modifications to the research procedures (e.g., method of data collection, nature or scope of information to be collected, changes in confidentiality measures, etc.), modifications that result in the inclusion of participants from vulnerable populations, and/or any change that may increase the risk or discomfort to participants. Changes to key personnel must also be approved. The purpose of review is to determine if the project still meets the federal criteria for exemption.

  Non-exempt research is subject to many regulatory requirements that must be addressed prior to implementation of the study. Conducting non-exempt research without IRB review and approval may constitute non-compliance with federal regulations and/or academic misconduct according to ISU policy.

  Detailed information about requirements for submission of modifications can be found on the Exempt Study Modification Form. A Personnel Change Form may be submitted when the only modification involves changes in study staff. If it is determined that exemption is no longer warranted, then an Application for Approval of Research Involving Humans Form will need to be submitted and approved before proceeding with data collection.

Please note that you must submit all research involving human participants for review. **Only the IRB or designees may make the determination of exemption**, even if you conduct a study in the future that is exactly like this study.

Please be aware that **approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **An IRB determination of exemption in no way implies or guarantees that permission from these other entities will be granted.**

APPENDIX B. "WHAT IS ENGINEERING?" SURVEY

What is an engineer?

What kinds of things does an engineer do? Select from the following list all examples of things that an engineer would do for his or her job.

- ☐ Develop better bubble gum
- ☐ Steer ships
- ☐ Install cable television
- ☐ Improve bandages
- ☐ Draw diagrams of new technologies
- ☐ Fix headlights on cars
- ☐ Fly airplanes
- ☐ Nail beams together for new houses
- ☐ Figure out how to package bottles so they don't break
- ☐ Drive trains
- ☐ Come up with ways to keep soup hot for a picnic
- ☐ Develop smaller cell phones
- ☐ Invent warmer kinds of cloth
- ☐ Drive motor boats
- ☐ Operate cranes
- ☐ Improve camera lenses
- ☐ Invent waterproof materials
- ☐ Design tools for surgery
- ☐ Improve a truck by putting new wheels on it
- ☐ Build chimneys out of bricks
- ☐ Design ways to clean polluted air
- ☐ Drive garbage trucks
- ☐ Figure out ways to explore the ocean
- ☐ Run machines for doctors and scientists
- ☐ Install wiring
- ☐ Fix computers
- ☐ Think about ways to clean the air
- ☐ Figure out what materials to use to make bridges
- ☐ Put shelves together in a store
- ☐ Design smaller kinds of computers
- ☐ Drive racecars on a racetrack
- ☐ Pour cement for new roads
- ☐ Measure how much weight materials can hold before they break
- ☐ Figure out how tall you can safely build towers
- ☐ Cut glass to make windows in buildings
- ☐ Pack furniture into boxes in a factory
- ☐ Repair cars

How important are each of the following activities to the work of an engineer?

	Not Important		Sort of Important		Very Important
Using math	O	O	O	O	O
Driving machines	O	O	O	O	O
Using models	O	O	O	O	O
Testing ideas	O	O	O	O	O
Building houses	O	O	O	O	O
Working as a team	O	O	O	O	O
Doing experiments	O	O	O	O	O
Solving problems	O	O	O	O	O
Sketching ideas	O	O	O	O	O
Repairing engines	O	O	O	O	O
Using their creativity	O	O	O	O	O
Understanding science	O	O	O	O	O
Reading about inventions	O	O	O	O	O
Using power tools to fix things	O	O	O	O	O
Using power tools to build things	O	O	O	O	O
Writing down their ideas	O	O	O	O	O
Fixing broken things for other people	O	O	O	O	O
Writing reports for other engineers	O	O	O	O	O
Brainstorming different ideas	O	O	O	O	O
Driving people from place to place	O	O	O	O	O
Telling other people what they find out	O	O	O	O	O